COST Action TU0901 – Building acoustics throughout Europe. Volume 1: Towards a common framework in building acoustics throughout Europe

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COST Action TU0901:
Integrating and Harmonizing Sound Insulation Aspects
in Sustainable Urban Housing Constructions

Building acoustics throughout Europe
Volume 1: Towards a common framework in building acoustics throughout Europe

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COST Action TU0901

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COST - European Cooperation in Science and Technology is an intergovernmental framework aimed at facilitating the collaboration and networking of scientists and researchers at European level. It was established in 1971 by 19 member countries and currently includes 35 member countries across Europe, and Israel as a cooperating state.

COST funds pan-European, bottom-up networks of scientists and researchers across all science and technology fields. These networks, called 'COST Actions', promote international coordination of nationally-funded research.

By fostering the networking of researchers at an international level, COST enables break-through scientific developments leading to new concepts and products, thereby contributing to strengthening Europe's research and innovation capacities.

COST's mission focuses in particular on:

- *Building capacity by connecting high quality scientific communities throughout Europe and worldwide;*
- *Providing networking opportunities for early career investigators;*
- *Increasing the impact of research on policy makers, regulatory bodies and national decision makers as well as the private sector.*

Through its inclusiveness, COST supports the integration of research communities, leverages national research investments and addresses issues of global relevance.

Every year thousands of European scientists benefit from being involved in COST Actions, allowing the pooling of national research funding to achieve common goals.

As a precursor of advanced multidisciplinary research, COST anticipates and complements the activities of EU Framework Programmes, constituting a "bridge" towards the scientific communities of emerging countries. In particular, COST Actions are also open to participation by non-European scientists coming from neighbour countries (for example Albania, Algeria, Armenia, Azerbaijan, Belarus, Egypt, Georgia, Jordan, Lebanon, Libya, Moldova, Montenegro, Morocco, the Palestinian Authority, Russia, Syria, Tunisia and Ukraine) and from a number of international partner countries.

COST's budget for networking activities has traditionally been provided by successive EU RTD Framework Programmes. COST is currently executed by the European Science Foundation (ESF) through the COST Office on a mandate by the European Commission, and the framework is governed by a Committee of Senior Officials (CSO) representing all its 35 member countries.

More information about COST is available at www.cost.eu.

Preface

Neighbour noise is a significant problem having had insufficient attention for decades, both for existing housing and new housing. Time had come to solve the challenges by establishing a common framework in building acoustics throughout Europe. As a consequence, the research network, COST Action TU0901 "Integrating and Harmonizing Sound Insulation Aspects in Sustainable Urban Housing Constructions" was established to initiate and support a process towards such framework.

COST TU0901 considered the main tool to be an acoustic classification scheme for dwellings – implying definition of a number of quality classes – combined with knowledge about housing constructions complying with the class criteria.

During the four years official lifetime of COST TU0901, close research cooperation and discussions have taken place between around 90 experts from 29 European countries and 3 overseas countries participating in COST TU0901. Most of the work was done in or through the three TU0901 working groups.

The findings from COST TU0901 are presented in two books with the joint main title "Building acoustics throughout Europe". Volume 1 describes the background, the current situation and the main findings from the working groups. Volume 2 consists of country chapters describing the national housing stock, construction types and related sound insulation performance in countries involved in COST TU0901.

We hope all the work presented herein will be used to meet our main objective, which is no other than providing "sustainable, quieter homes all over Europe", and maybe beyond.

The cooperation initiated in COST TU0901 will continue in many ways, including standardization groups and research projects, thus supporting the process towards quieter European homes.

April 2014
Birgit Rasmussen – Chair of COST TU0901
María Machimbarrena – Vice Chair of COST TU0901

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Introduction

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Introduction

Most European countries have regulatory sound insulation requirements for dwellings, and classification schemes exist in several countries. However, sound insulation descriptors, requirements and class criteria present a high degree of diversity and, unfortunately, there is no sign of increasing harmonization, rather the contrary. The diversity causes confusion for the building industry and is an obstacle for trade, development and exchange of experience and construction data.

COST Action TU0901 was established to initiate changes to this situation to the benefit of people in their everyday life and for the building industry. It is believed that although regulations are a national issue within each country, if all European countries used the same descriptors and had a joint acoustic classification scheme for dwellings, each country could select a class for regulations, and all involved sectors would in the long run benefit from the harmonization. Furthermore, it is difficult to compare perceived satisfaction or annoyance related to neighbour noise for people in different countries, because questionnaires for field surveys differ considerably.

On top of the above-mentioned challenges, a general focus on energy savings and sustainable constructions has in some cases led to development of constructions with potentially significant acoustic problems. At the same time home entertainment systems have developed from simple radios and television sets in the sixties to sophisticated home theatre systems with powerful rhythms and low-frequency musical content, implying a need for higher sound insulation.

Considering the situation described above, the TU0901 objectives were defined as follows:

Main objectives

- *Propose harmonized descriptors for airborne and impact sound insulation.*
- *Propose a European acoustic classification scheme for dwellings.*

Secondary objectives

- *Include low frequency range adequately*
- *Prepare a uniform questionnaire on annoyance by neighbour noise*

- *Deduce some kind of correlation between sound insulation and annoyance*
- *Establish a catalogue of sound insulation data for construction solutions found in the different participating countries*
- *Produce an on-line compendium on good workmanship practice*

Detailed information on the scope and aims of TU0901 is found in the Memorandum of Understanding of the Action, which can be found at http://www.cost.eu/domains_actions/tud/Actions/TU0901

The European Action COST TU0901 has been running for 4 years 2009-2013, stimulating research, collecting experiences from 29 countries in Europe and 3 overseas countries and joining efforts to find a consensus proposal both for acoustic descriptors and an acoustic classification scheme for housing.

The work has been distributed between three working groups, all of them contributing to the common objectives from different perspectives:

- *WG1: Harmonized sound insulation descriptors and classification schemes in Europe*
- *WG2: Subjective evaluation of sound insulation - Laboratory tests and harmonized field surveys*
- *WG3: Design and acoustic performance of building constructions for multi-storey housing*

Summarizing all the work done, all the information collected and all achievements in a book is not an easy task. The contents have been distributed in chapters dealing with the most relevant issues being addressed during the lifetime of TU0901 and is presented in such a way that the first two chapters focus on the problems and state of the art prior to the beginning of the Action and the remaining chapters contain a description of the work done and main outputs.

Chapter 1 summarizes the "state of the art" concerning building stock in Europe and gives an overview of the relevance of the "building acoustics" problem.

Chapter 2 summarizes the "state of the art" concerning existing sound insulation descriptors, regulatory requirements and acoustic classification schemes in Europe.

Chapters 3 and 4 deal with one of the two main objectives of TU0901: Proposed harmonized descriptors and translation between existing national criteria to proposed new descriptors. Chapter 5 describes the TU0901 proposal for an acoustic classification scheme that could in the long run be adopted as a European or even international scheme and summarizes the work done to prepare the proposal.

The Chapters 6 to 8 deal with subjective perception of neighbour noise in dwellings. The experience of developing a harmonized questionnaire to be used all over Europe for assessing annoyance due to neighbouring noise is summarized in Chapter 6, which also includes findings from the preliminary use of the questionnaire in some participating countries. Chapter 7 deals with the task of developing guidelines for performing listening tests related to building acoustics, and finally Chapter 8 focuses on the challenge of correlating objective and subjective sound insulation.

Much of the work done in WG3 is summarized in Chapters 9 to 11. Chapter 9 focuses on design and performance of existing building techniques all over Europe, whereas Chapter 10 summarizes the information provided by participating countries concerning common errors and good practice at design and workmanship stages. Chapter 11 provides an overview of the range of construction types found across Europe.

Conclusions and suggestions for the next steps and for future research issues are found in Chapter 12.

Although each chapter is signed by the indicated authors, it is important to mention that most of the outcomes would not have been possible without the input of the many contributors from all participating countries. It is fair to give special credit to WG1 members for contents of Chapters 3, 4 and 5, WG2 members for contents of chapters 6, 7 and 8, WG3 members for Chapters 9 and 10, and all COST TU0901 members for the country information found in the COST TU0901 e-book, Volume 2.

All members of COST TU0901 are listed in the Annex, and information about working group members and leaders is given.

Making proposals for harmonized sound insulation descriptors and a classification scheme is a long process, since acoustics and building problems and solutions differ widely across Europe. Nevertheless, several fruitful discussions have taken place, and preliminary consensus has been established, and –very important– the minds of the involved experts have been prepared for future changes.

During the TU0901 Action period, there has been contact or cooperation with three other COST Actions, namely FP0702 (Acoustics for Timber based Lightweight Buildings), TU0701 (Improving the Quality of Suburban Building Stock), TD0804 (Soundscapes).

At Forum Acusticum 2011, EuroNoise 2012 and InterNoise 2013 structured sessions have been organized with more than 50 conference papers in total from TU0901 members. Overview and abstracts of these papers and from several other conferences have been collected in a separate document made available at http://www.costtu0901.eu.

Information concerning other activities and outputs of COST TU0901 can be found at http://www.costtu0901.eu

The main objectives of TU0901 –proposals for harmonized sound insulation descriptors and for a European acoustic classification scheme for dwellings– are both issues of high relevance for international standardization. Several TU0901 members are participating actively in the relevant acoustic standardization working groups in ISO/TC 43/SC 2 and CEN/TC 126, where lively discussions about sound insulation descriptors have taken place the last few years. The discussions are not initiated by TU0901, but happening in parallel due to problems and needs in real peoples' lives in real homes. Especially in the case of new housing, where constructions are expected to be optimized sufficiently, these issues naturally come to the attention of acoustic experts. The TU0901 findings have already been presented to the ISO/TC43/SC2 and CEN/TC126 building acoustic technical committees aiming at standardization and will be discussed in more detail in the relevant ISO and CEN working groups.

Main results from the TU0901 working groups are found in the present TU0901 e-book, Volume 1, which is an extended version of the printed book published before the TU0901 Final Conference in Copenhagen on 3 December 2013. Country chapters about the housing stock and construction types across Europe –and two overseas countries– are found in the TU0901 e-book, Volume 2.

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Building acoustics throughout Europe

Volume 1: Towards a common framework in building acoustics throughout Europe

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Profiling Existing and New Build Housing Stock

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CHAPTER 1 Profiling Existing and New Build Housing Stock

1.1. Introduction

This chapter discusses the population profiles and existing housing stock across Europe of individual countries which have participated in this COST Action TU0901 study. The diversity of housing types is also reviewed and the relationship between detached, attached (terraced/row) and apartment housing found across many countries. This allows some approximations to be calculated for the number of neighbours in these countries with adjoining walls and floors in attached housing.

Current construction techniques and common building materials are described briefly in this Chapter. These issues are covered in more detail in Chapter 10 and the planned e-book which is to feature constructions and typical sound insulation performance for each country.

Finally, the aspect of quality of life for home occupants is discussed and the importance of good design, construction and monitoring.

1.2. Population in Europe

1.2.1. Comparison to rest of the world

In 2012 the European Union of 27 countries 'EU27' and rest of the Europe accounted for 10-11% of the world population (Eurostat, 2013). The EU27 grouping alone accounts for 512 million people as shown in figure 1.1.

1.2.2. Populations included within COST Action TU0901

Whilst maps of Europe such as Figure 1.2 differentiate on the basis of economic area or trade links, the aspects of housing, quality of life and sound insulation affect the populations in all these countries irrespective of borders.

In addition, many countries in other parts of the world also share and co-operate via such COST Actions and during the period of TU0901 Action country representatives from New Zealand, Australia and Canada attended meetings. As such the country populations represented during this Action have totalled over 649 million people.

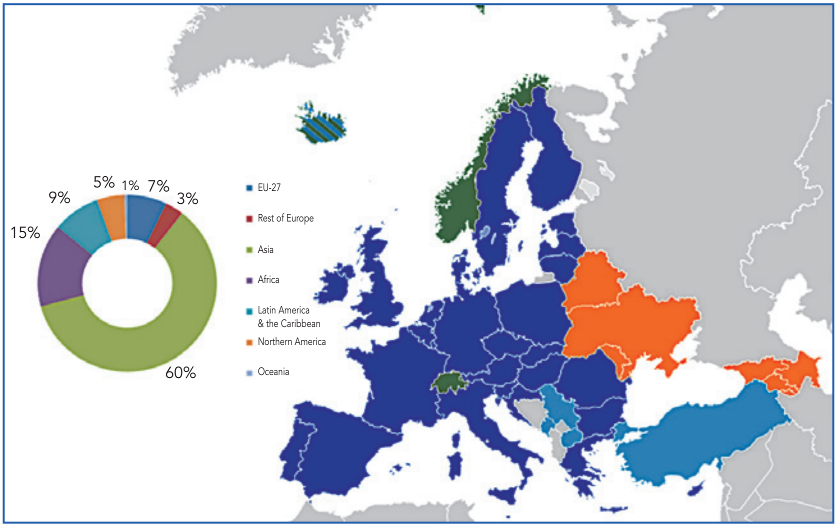

Figure 1.1. *(Left) – Global comparison of EU27 and (rest of EU) population.*
Figure 1.2. *(Map) – EU28, EFTA and Eastern Partnership map of countries (2013).*

1.3. Housing in European Countries

Table 1.1 shows the countries represented during this COST Action participating in meetings, correspondence and their relative population sizes recorded in 2012 or 2013.

To consider the housing stock in Europe in relation to sound insulation, different types of sound transmission and the proportion of occupants which may be experience sound transmission it is useful to know the type of housing found in each country. Using a combination of Eurostat statistics (2013) and information gathered during COST Action (TU0901 Berlin, 2010) this section describes the proportion of population which inhabit:

- Detached housing
- Attached (row/terraced, semi-detached) housing
- Apartment (flatted) housing

1.3.1. Housing Types in Europe

Table 1.2 illustrates the proportion of housing in various European countries which have been involved in this COST Action. It can be seen

Table 1.1. Participating countries in COST Action TU0901 and their respective approximate populations (recorded in 2012/2013).

1	Germany	80,640,000		18	Serbia	7,203,000
2	Turkey	75,600,000		19	Denmark	5,612,000
3	Unit. Kingdom	64,231,000		20	Finland	5,436,000
4	France	63,820,000		21	Slovakia	5,413,000
5	Italy	59,789,000		22	Norway	5,077,000
6	Spain	46,958,000		23	Croatia	4,258,000
7	Poland	38,548,000		24	Lithuania	2,956,000
8	Romania	19,858,000		25	Macedonia	2,066,000
9	Netherlands	16,795,000		26	Slovenia	2,062,000
10	Belgium	11,162,000		27	Estonia	1,283,000
11	Greece	10,758,000		28	Malta	419,000
12	Portugal	10,609,000		29	Iceland	324,000
13	Czech Rep.	10,519,000			***sub-total***	***587,437,000***
14	Hungary	9,894,000			Canada	34,880,000
15	Sweden	9,595,000			Australia	22,680,000
16	Austria	8,477,000			New Zealand	4,400,000
17	Switzerland	8,075,000			**TOTAL**	**649,397,000**

that there is a wide variation in the proportion of inhabitants across these three main housing type groups.

The proportion of population living in each country for detached housing varies from 6% (Malta) to 72% (Croatia) with an average of 41%, with the relative proportions in each country shown in Figure 1.3.

Figure 1.4 provides examples of the diversity of attached houses involving row, terraced and semi-detached housing. The proportion of population living in attached houses varies from 2% in Romania to 61% in the Netherlands, with an average of 18%. A comparison between countries is shown in Figure 1.5.

Figure 1.6 illustrates examples of apartment or flatted development housing found in Europe. The proportion of population varies from 8% in Norway to 65% in Spain, with an average of 40%. A comparison between countries is shown in Figure 1.7.

The significant variation for all three main housing types is also shown as a collective summary in Figure 1.8.

Table 1.2. *Percentage of population and total number of persons living in various housing types for each COST Action country.*

	ATTACHED HOUSING				DETACHED HOUSING		
Country	Flats / Apartments [%]	Semi-detached row, terraced housing [%]	TOTAL % of attached houses [%]	TOTAL number of people living in ATTACHED housing [persons]	Single unit housing (detached) [%]	TOTAL number of people living in DETACHED housing [persons]	Other [%]
Austria	42.2	13.7	55.9	4,738,643	43.2	3,662,064	1
Belgium	20.6	41.9	62.5	6,976,250	36.9	4,118,778	0.5
Croatia	21.8	6.3	28.1	1,196,498	71.7	3,052,986	0.1
Czech Republic	52.4	10.1	62.5	6,574,375	37.3	3,923,587	0.2
Denmark	37	14.8	51.8	2,907,016	44.4	2,491,728	3.7
Estonia	64.5	4.9	69.4	890,402	30	384,900	0.5
Finland	33.2	19	52.2	2,837,592	47.1	2,560,356	0.6
France	33	22.3	55.3	35,292,460	44.6	28,463,720	0.1
Germany	53.6	16.1	69.7	56,206,080	28.8	23,224,320	1.6
Greece	59.6	8.5	68.1	7,326,198	31.8	3,421,044	0.1
Hungary	29.2	5.4	34.6	3,423,324	64.7	6,401,418	0.7
Iceland	45.4	19.1	64.5	208,980	35	113,400	0.5
Italy	48.4	26.7	75.1	44,901,539	24.4	14,588,516	0.5
Lithuania	57.4	6.8	64.2	1,897,752	35.3	1,043,468	0.5
Macedonia	38	2	40	826,400	60	1,239,600	0
Malta	47.2	46.5	93.7	392,603	5.6	23,464	0.7
Netherlands	18.4	61.2	79.6	13,368,820	16	2,687,200	4.4
Norway(1)	7.5	19.2	26.7	1,355,559	62.3	3,162,971	11.1
Poland	46.7	4.4	51.1	19,698,028	48.8	18,811,424	0.1
Portugal	39.7	19.2	58.9	6,248,701	40.7	4,317,863	0.4
Romania	37.7	1.5	39.2	7,784,336	60.8	12,073,664	0
Serbia	(Note 2)	(Note 2)	56	4,033,680	44	3,169,320	0
Slovakia	48.4	2	50.4	2,728,152	49.5	2,679,435	0.2
Slovenia	28.9	4	32.9	678,398	66.8	1,377,416	0.3
Spain	64.9	21	85.9	40,336,922	14.1	6,621,078	0.1
Sweden	40.1	8.6	48.7	4,672,765	50.9	4,883,855	0.3
Switzerland	60.3	12.2	72.5	5,854,375	24.5	1,978,375	3
United Kingdom	14.7	59.3	74	47,530,940	25.8	16,571,598	0.2
			TOTAL	330,886,788			

Notes: (1) Norway has higher levels of 'other' classification, as such this may affect reporting of semi-detached and row housing. (2) In the case of Serbia the classifications of attached houses and apartments was not recorded separately.

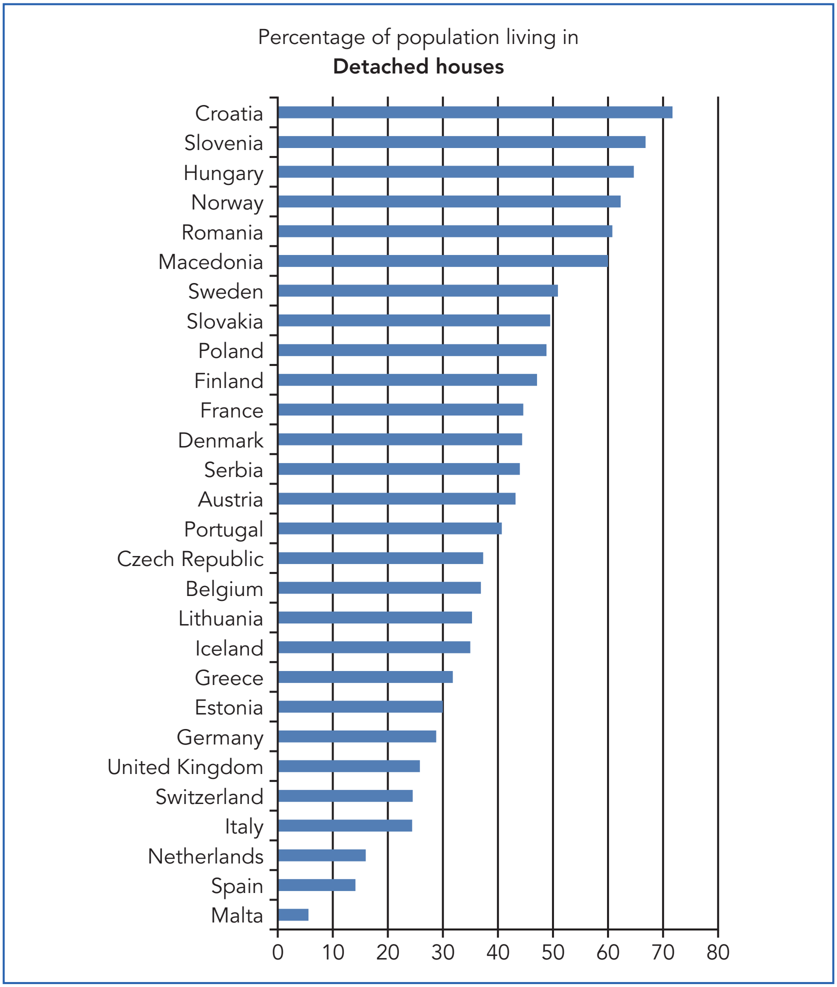

Figure 1.3. *The percentage of population living in detached housing in each country (Eurostat, 2013).*

In some cases the housing types did not fall within the three primary categories and is noted as 'other'.

1.3.2. Estimated Quantity of Population in Attached Housing

Using the proportion of population for each housing type and the population for each country it is possible to determine the approximate number of people (see table 1.2) living in attached housing involving row, terraced, semi-detached and flats (apartments). The estimated total number of people who thus have separating structures present in their homes for the 28 countries is approximately 331 million inhabitants.

Closer inspection of such statistics illustrates factors relating to actual number of flatted / apartment dwellings and regional variations in each country. For example in Figure 1.9 whilst the UK shows 15% of the population living in apartments, the total percentage share of apartments in the UK for the whole housing stock is 19%. Variations across the UK four nations show that Scotland has a high proportion of housing stock as flats / apartments and Wales and Northern Ireland considerably lower.

1.4. Current Common Construction Methods in Europe

For much of the twentieth century the construction styles and methods for attached new housing have evolved using on site construction methods and local sourced materials. The move from large solid wall constructions for some EU countries to cavity walls occurred in the early 1920's and 30's

Figure 1.4. *Examples of attached houses such as terraced (row) and semi-detached found in participating COST Action countries.*

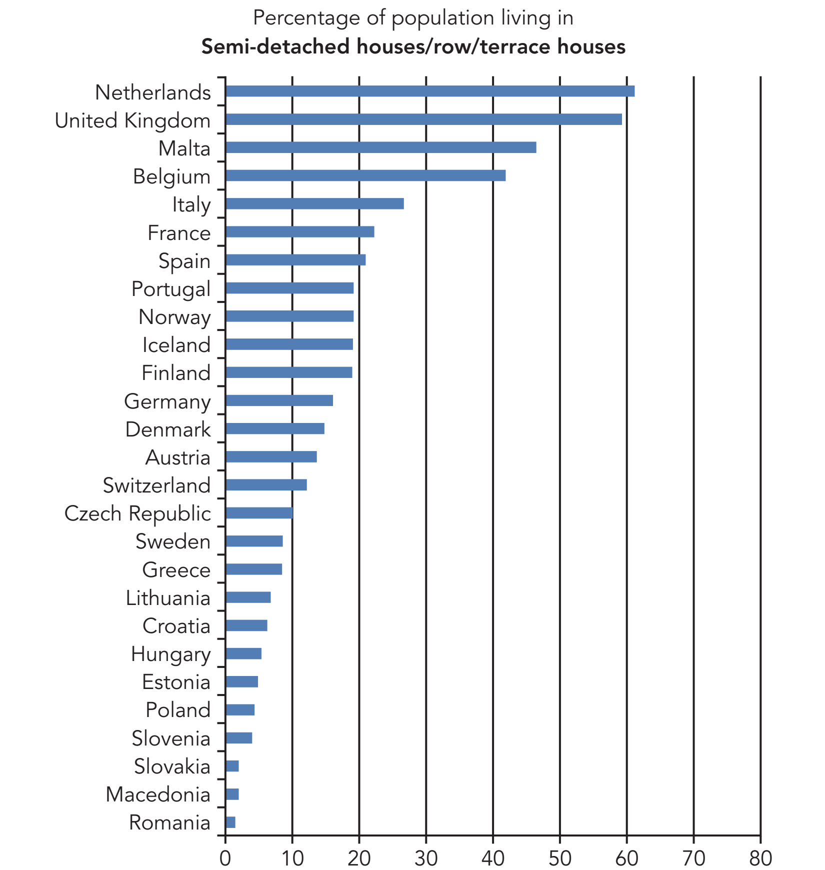

Figure 1.5. *The percentage of population living in row (terraced) or semi-detached housing in participating COST Action countries (Eurostat, 2013). Note: Norway has higher levels of 'other' classification, as such this may affect reporting of semi-detached and row housing.*

with advancements in mineral wool, gypsum board, timber construction, brick and concrete block work.

During the 1950's many EU countries then embarked on high rise multi storey apartments involving concrete and steel frames. More recently, for northern European countries the development of multifamily lightweight steel and timber frame dwellings has also evolved significantly.

Figure 1.6. *Examples of apartments (flats) found in participating COST Action countries.*

The diversity and choice of materials used across European countries has predominantly been cost driven. However, more recently in the 1980s and 1990's the increase in performance requirements such as energy performance and sound insulation has resulted in a stronger combined focus towards cost and technical building performance. This has also led to more trans-European supply chains and a consolidation of multi-national product manufacturing companies.

The beginning of the 21st century may be regarded in future as a turning point in terms of a greater emphasis towards more sustainable construction. The scale of regulation changes during the last decade has been unprecedented for many EU countries. However, the two decades

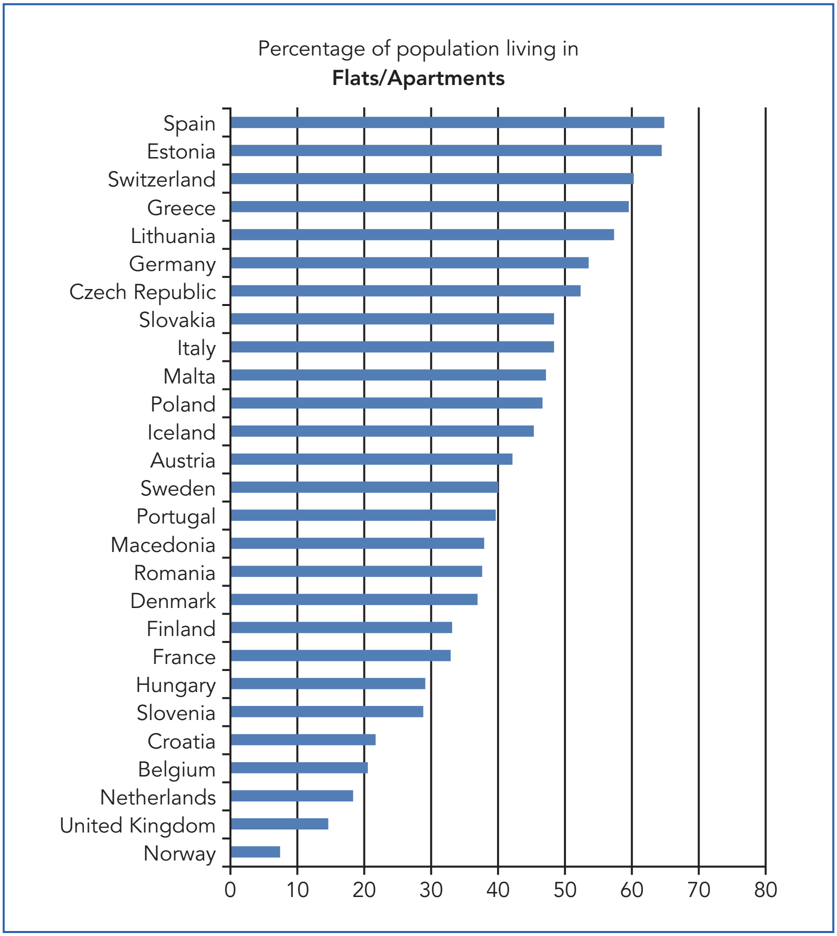

Figure 1.7. The percentage of population living in apartments (flats) in participating COST Action countries (Eurostat, 2013). Note: Norway has higher levels of 'other' classification, as such this may affect reporting of semi-detached and row housing.

(2010-2030) will bring about some of the most comprehensive and challenging changes to performance specifications and materials to be adopted. The forthcoming requirements for low and zero carbon housing both in individual countries and also via EU Directives will change the landscape of the knowledge base requirements and ultimately the future houses and apartments which are built.

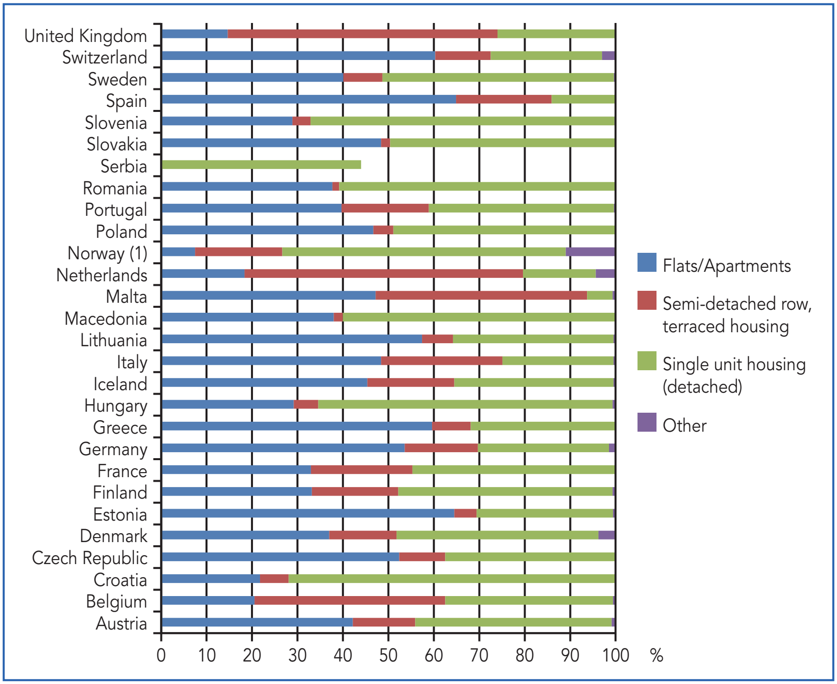

Figure 1.8. *The percentage of population living in all main types of housing diagrammatically presented (Eurostat, 2013). Notes: (1) Norway has higher levels of 'other' classification, as such this may affect reporting of semi-detached and row housing. In the case of Serbia the classifications of attached houses and apartments was not recorded separately and could therefore not be represented here.*

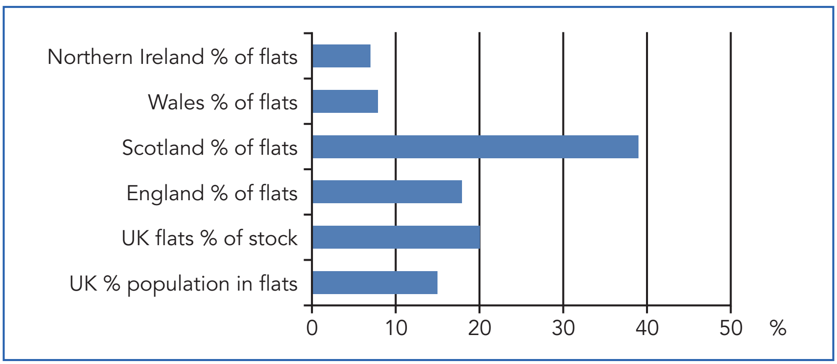

Figure 1.9. *Compares variations within one country (example UK) of the variation of flats/apartments within housing stock (Smith et al, 2005).*

As a result, the technical compatibility requirements between different building regulations will be a key factor in the successful delivery of new housing systems and building technology products. The interaction between each country's regulatory and guidance requirements for structure, energy performance, sound insulation and environmental impact will dictate the conduction materials, systems and designs to be built.

1.4.1. Classification of core structural elements

The classification of current structural construction products for attached housing in European countries is not straightforward. For the purposes of this publication and for simplification the following categorisation could be assimilated:

- *Masonry / Block work based* – involving the use of clay, terracotta, aggregate or calcium silicate based structures
- *Timber based* – involving timber frame (open and closed panel), post and beam, cross laminated timber (CLT) or massive timber elements and engineered wood product systems such as engineered I-joists or metal web joists
- *Steel based* – involving lightweight steel frame, high rise steel frame with composite concrete deck systems
- *Concrete based* – involving in-situ concrete, precast beams, slab and panel, insulated concrete formwork
- *Hybrid based* – involving block work walls with beam and block floors, block work walls with timber floors, steel frame and timber based panels, concrete or steel frame with insulated metal cladding or curtain walling.

Figure 1.10 Shows examples of current construction systems for masonry and block work wall construction.

Figure 1.11 provides examples of current concrete floor constructions found across Europe.

Figure 1.12 provides examples of current timber and steel frame construction systems found in European housing.

1.5. Combinations of Apartment Wall and Floor Combinations

Wall and floor systems commonly found in current apartment constructions Europe vary significantly and examples are shown in Figure 1.14.

Figure 1.10. *Example of masonry and concrete wall types used in European separating walls. (left to right: cellular block, solid block, thin joint aircrete blocks, insulated concrete formwork, large hollow blocks, full height precast wall panels, diverse perforated clay blocks).*

Figure 1.11. *Examples of various precast, beam and block and in-situ composite separating floor types found in European countries. (left to right: full depth beam and block, shallow beam and block, hollowcore precast, in-situ beams with clay block infill, omni-floor system, lightweight insulated blocks with in-situ pour, deep profiled steel deck with in-situ concrete, deep hollowcore precast and shallow metal deck with in-situ concrete).*

Figure 1.12. *Examples of timber and lightweight frame wall and floor structures found in European countries. (left to right: open metal web joists, engineered I-joists, open timber web joists, solid joists, twin sheathed party walls, non-sheathed party walls, metal I stud twin party walls, cross laminated timber panels for walls and floors and metal C stud sections).*

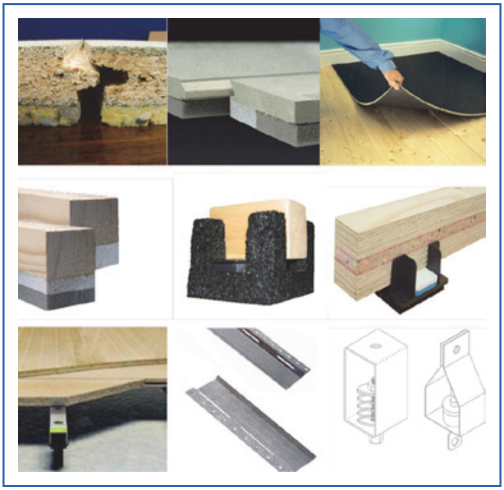

Figure 1.13. *Examples of specialist acoustic construction products for improved sound insulation. (Left to right: shallow floor deck using recycled foam, dual foam shallow decks, bonded soft floor coverings, resilient flooring battens, rubber crumb based floor cradles, deep floor cradle systems, raised access floors, resilient bars and acoustic ceiling hangers).*

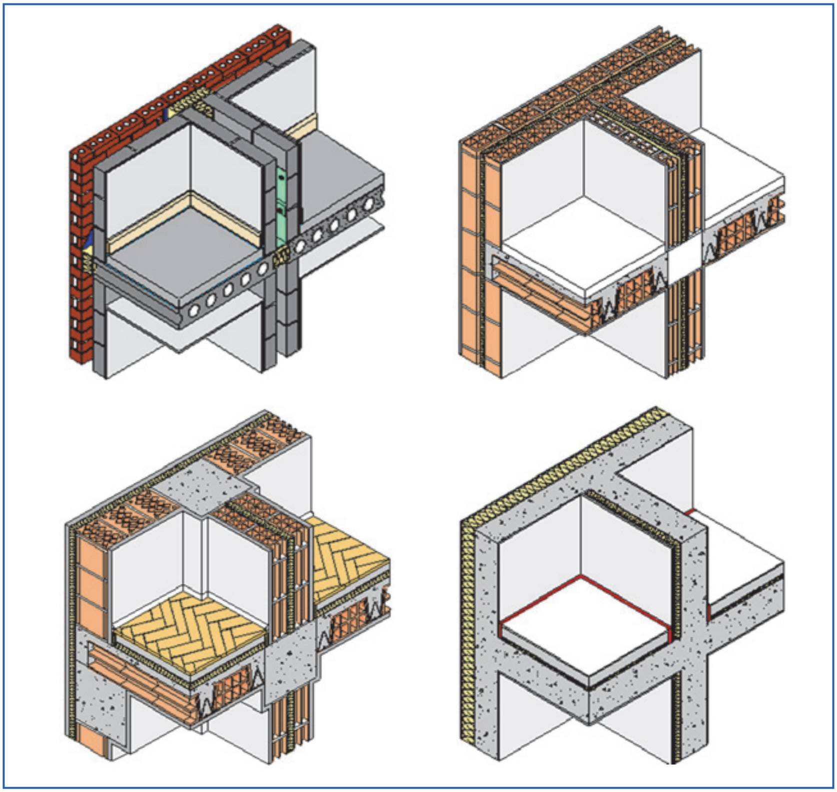

Figure 1.14. *Examples of concrete, blockwork and clay based wall and floor systems built in Eurpean countries:Top left – UK; Top Right – Italy; Bottom left – Macedonia; Bottom right – Switzerland. (Wood, TU0901 Florence, 2010).*

1.6. Typical Sound Transmission Paths in Housing

In attached houses, each dwelling has separating walls, and for flats or apartments, separating walls and floors will both be present.

The term **'separating wall'** also known as a party wall divides two separate homes. A mid-terraced house shares separating walls with two neighbouring houses. A flat may share one or two separating walls with neighbouring dwellings but may also have a separating wall to a common public hall or access communal stairway

The term **'separating floor'** is only used for flats (apartments). It means the floor between two apartments, one above the other. In unusual situations it could mean the floor between a corridor and a dwelling below. It does not refer to the intermediate (internal) floor in a house or maisonnette.

Sound transmission between attached housing can transmit directly through the wall or floor known as '*direct sound transmission*'. However, there are additional sound transmission pathways known as in-direct or flanking pathways. For example a separating wall construction may be the same over its full height (foundation to roof). As a separating wall can be structurally connected to foundations, floors, internal walls, roof and external walls, each of these junctions and their material make-up influences the sound insulation properties of the wall. Sound that is able to transmit between attached dwellings at these junctions is commonly referred to as *flanking sound transmission*. This may often have a controlling influence on the separating wall's sound insulation performance.

Thus the sound insulation performance of a separating wall between two attached houses can vary at each floor level due to the different structural junctions, construction materials used and direct and flanking pathways as shown in Figure 1.15.

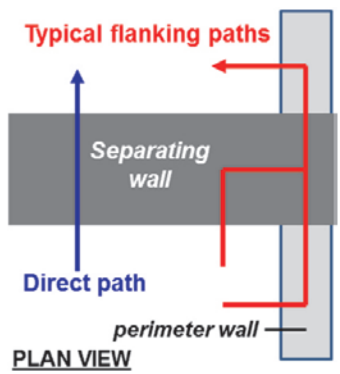

Figure 1.15. *Example of 'direct' and 'flanking' transmission pathways for a separating wall.*

1.7. Design and Construction of Homes and Quality of Life

1.7.1. Sound transmission effects on occupants

General noise exposure due to sound transmission from attached housing may impact on the householder's health and wellbeing. Sound transmission from adjacent houses may act indirectly as a catalyst towards detrimental health effects through a variety of mechanisms. The extent of the effect on health is dependent on an individual's sensitivity, health profile, circumstance and perception of, or control over the noise problem. Non-auditory effects (Stansfield *et al*, 2000) of domestic noise can be classified as:

- sleep disturbance
- annoyance
- activity disturbance
- emotional response

The disturbance to sleep by noise depends on the stimulus (type of noise, intensity, duration, repetition etc.) on the stage of sleep at which the disturbance occurs, on the environment, as well as on individual variables such as age or state of health.

Noise (or sound) that is unavoidable, unnecessary or emotive is often the most annoying. Activities such as sleeping, reading (studying) and listening to television/radio are the common noise-disrupted activities. Sound transmission between attached housing and its non-auditory effects may cause increasing tensions between neighbours and lead to disputes, which may result in a few cases to physical assaults.

The intrusion of noise into a home influences a range of aspects of an occupant's home life and as such it is very important to design and construct homes which can at least attenuate sounds from normal living activities.

Occupants' perception of noise and their response or reaction to sound transmission from adjoining dwellings varies. Their reaction to neighbour noise (sounds) may be influenced by the type of relationship that already exists with their neighbours. Some occupants may accept that it is not possible to prevent all sounds transmitting into their house, but would not find it acceptable to hear moderate levels of noise from televisions and radios, conversations and general living.

1.7.2. Frequently recurring complaints

There are a number of frequently recurring complaints concerning the types of noise people can hear from the adjoining dwelling. In addition, a diverse range of sound frequencies or pitch may be involved. Table 1.3 provides a summary of the types of sounds from adjoining dwellings and frequency range (or pitch) involved.

Table 1.3. *Potential sound sources in housing, associated airborne or impact sources and typical frequency ranges involved.* Frequencies: low = 40-200Hz; mid = 250-1KHz; high = 1.25KHz – 3KHz; all = wide range of frequencies. *(Smith* et al, *2005).*

Potential sound (noise) sources in attached housing	Airborne Sound	Impact Sound	Sound frequencies influenced
Teenagers or adult voices	■		mid-high
TV	■		mid-high
Doors closing		■	low-mid
Radio / Music	■		all
Domestic equipment	■	■	all
Plugs being inserted into sockets		■	low-mid
Switches being turned on or off		■	mid
Cupboard doors closing		■	low-mid
Services noise (e.g. downpipes, water pumps)	■		all
Footsteps		■	low-mid
Children playing	■	■	all
D.I.Y	■	■	all
Dogs barking	■		low-mid

1.8. Conclusion

This chapter has described the range of house types found across different European countries and the types of construction systems currently being used in new homes. Annually across these countries the construction industry may build over 1.5 million homes every year.

Over the coming decades millions more homes will be built across Europe. To deliver the quality of life expected by so many occupants and to address the changing lifestyles of the 21st century it will be necessary to review the criteria by which we assess sound insulation.

Any such changes would require the assessment of existing regulations, performance criteria and methodologies to enforce good practice in constructions and ensure criteria are met and ultimately the future occupant evaluation and quality of life benefits. Sound transmission is an aspect of life which is possible to attenuate. If not correctly dealt with it can provide an annoyance factor all year round, random in its source and timing which can reduce the quality of life for any occupant irrespective of age.

Good design and construction, with adequate and appropriate regulation, guidance and monitoring has the potential to deliver so many benefits for future generations.

1.9. References

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[2] http://www.costtu0901.eu/

[2] Berlin Meeting, Working Group 3, COST Action TU0901, 2010.

[3] R.S. Smith, J.B. Wood and R.G. Mackenzie. Housing and Sound Insulation, Scottish Government. Arcamedia, Edinburgh, UK, 2005.

[4] J.B. Wood and R.S. Smith. Florence Meeting, Working Group 3, COST Action TU0901, 2010.

[5] S. Stansfield, M. Haines and B. Brown. Noise and health in the urban environment. London, 2000.

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Building acoustics throughout Europe

Volume 1: Towards a common framework in building acoustics throughout Europe

2

Existing Sound Insulation Performance Requirements and Classification Schemes For Housing Across Europe

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CHAPTER 2 Existing Sound Insulation Performance Requirements and Classification Schemes For Housing Across Europe

2.1. Introduction

Regulatory sound insulation requirements for dwellings exist in more than 30 countries in Europe. Classification schemes exist in several countries. In some countries, sound insulation requirements have existed since the 1950s. The first classification schemes for dwellings were implemented in the early 1990s.

Findings from comparative studies of regulatory sound insulation requirements in Europe and sound classification schemes show that sound insulation descriptors, regulatory requirements and classification schemes in Europe represent a high degree of diversity. Unfortunately, there is no sign of increasing harmonization, rather the contrary, i.e. evidence for an even more diverse situation in Europe. The studies conclude that harmonization is needed for descriptors and sound insulation classes to facilitate exchange of data and experience between countries and to reduce trade barriers. Most important is, however, that review of sound insulation requirements should be encouraged in several countries to adapt regulations to current construction trends and peoples' needs for health, wellbeing and comfort. In countries having no requirements, a change process towards decision and implementation of requirements should be initiated.

Looking into the future, harmonization of sound insulation requirements seems unrealistic. However, by preparing a harmonized European classification scheme with a number of quality classes, member states could select a "harmonized" class fitting the national needs and conditions.

This chapter will summarize the background, discuss the present situation in Europe and describe the joint efforts to reduce the diversity in Europe, thus supporting and initiating – where needed – improvement of sound insulation of new and existing dwellings in Europe to the benefit of the inhabitants and the society.

2.2. The need for sound insulation in housing

Social surveys in several European countries have shown that occupants of multi-storey housing are considerably annoyed by noise from neighbours' activities. The World Health Organisation (WHO) defines health as "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity", see [1]. Based on this definition, noise effects on health should not simply be understood as the adverse physical effects due to noise exposure, but also as disturbance of well-being, i.e. psychological effects of noise, which in the long term may lead to adverse physical effects. WHO has identified a considerable number of specific adverse health effects caused by environmental noise, see [2]. These effects can be medical conditions, but can also include sleep disturbance, stress etc.

The relevance of the sound insulation issue is illustrated in Figure 2.1 (ref. [3]) showing the amount of serious noise annoyance in national surveys in three EU countries, representing about 1/3 of the total EU population. In spite of uncertainties due to different methodologies (including questionnaires) applied for the surveys, the author of [3] concluded that the neighbour noise problem in Europe is significant. In [4], results from different social surveys are included, and the shortcomings due to inconsistent questionnaires in different countries are described. Neighbour noise has been addressed in a large pan-European LARES study (Large Analysis and Review of European housing and health Status) coordinated by WHO/Europe. The WHO LARES study included eight European cities, and the purpose was to evaluate the health impact of housing conditions. Results are found at the WHO website [2].

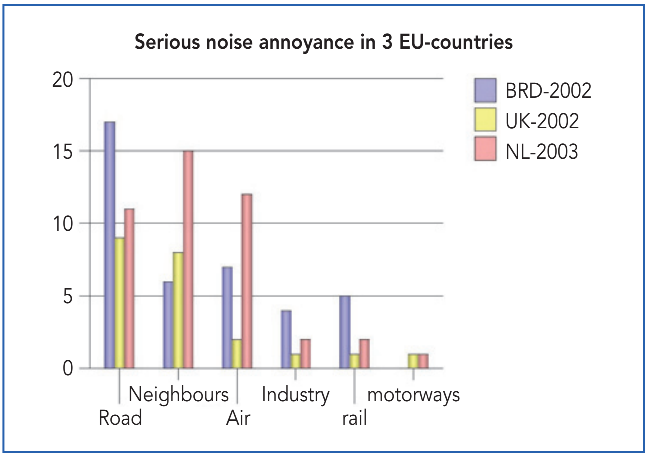

Figure 2.1. Sources of serious noise annoyance (% of inhabitants) in three EU countries. Ref: Martin van den Berg, 2004, [3].

When ranking annoyance from different noise sources, road traffic noise is the most dominant source, followed by neighbour noise. Based on statistics about populations [5] and findings from noise annoyance surveys (see eg Figure 2.1 or [4]), it seems that more than 50 million Europeans are exposed to neighbour noise causing adverse effects on quality of life. Quotes from the WHO LARES study and more detailed references are found in [6].

To keep towns and cities attractive, homes in multi-storey housing must be attractive for a variety of people and offer "quietness". Thus, new housing must meet the needs of the people and offer comfort. Also for existing housing, sound insulation aspects should be taken into account, especially when renovating housing. The challenge is huge, and knowledge exchange between countries is highly needed.

Comparative studies of sound insulation descriptors and regulatory requirements (2008) in Europe are described in [6-7] and sound classification schemes described in [8-9]. A high degree of diversity is found for descriptors, level of requirements and classification schemes in Europe, thus impeding exchange of experience of housing design and construction details for different levels of sound insulation. The need for harmonization is emphasized in [6-7] and several research initiatives suggested.

The situation in Europe is summarized in Section 2.3 for sound insulation descriptors and in 2.4 for regulatory requirements. An overview of classification schemes is found in Section 2.5. The need for harmonization in Europe, tools for upgrading, implementation and enforcement of requirements are described in Section 2.6. The harmonization efforts and results through COST Action TU0901, [10], are described in this book. This chapter – like COST TU0901 – focuses on neighbour noise and sound insulation between dwellings.

2.3. Sound insulation descriptors in Europe

Building acoustic requirements for dwellings now exist in more than 30 countries in Europe. In some countries, national sound insulation requirements have existed since the 1950s. Sound insulation requirements are expressed by descriptors defined in standards. Within building acoustics, ISO standards are implemented as European (EN) standards and national standards.

The international descriptors for evaluation of airborne and impact sound insulation are defined in ISO 717. Table 2.1 provides a historical overview of ISO 717.

Table 2.1. Historical overview of ISO 717 standards with indication of main characteristics.

1968	ISO/R 717:1968, "Rating of sound insulation for dwellings" (first edition, 7 pages)	Field descriptors: I_a, I_i 8 dB rule
1982	ISO 717:1982, "Acoustics - Rating of sound insulation in buildings and of building elements" Part 1: Airborne sound insulation in buildings and of interior building elements Part 2: Impact sound insulation Part 3: Airborne sound insulation of facade elements and facades	Laboratory & field: Part 1: R_w, R'_w, D_w, $D_{nT,w}$ Part 2: $L_{n,w}$, $L'_{n,w}$, $L_{nT,w}$ Part 3: Several symbols No 8 dB rule, but unfavourable deviations more than 8 dB shall be reported
1996	ISO 717:1996, "Acoustics - Rating of sound insulation in buildings and of building elements" Part 1: Airborne sound insulation Part 2: Impact sound insulation	Several spectrum adaptation terms: – C, C_{tr}, C_I – Various frequency ranges 50/100-3150/5000 Hz (four ranges)
2013	ISO 717:2013, "Acoustics - Rating of sound insulation in buildings and of building elements" Part 1: Airborne sound insulation Part 2: Impact sound insulation	Same main characteristics as for 1996. Amendments about rounding rules incorporated. Allow weighting steps of 0.1 dB to be used for expressing uncertainties. References to measurement methods/equations updated.

The single-number quantities and the spectrum adaptation terms are derived from values measured according to ISO 140 [12]. The spectrum adaptation terms in ISO 717 [11] have been introduced to take into account different spectra of noise sources. Table 2.2 describes the intended use of spectrum adaptation terms according to ISO 717.

In Table 2.3 is found an overview the basic 1/3 octave ISO 717 field descriptors (single-number quantities) and the spectrum adaptation terms intended for specification and test of:

- Airborne sound insulation between dwellings
- Airborne sound insulation for facades
- Impact sound insulation between dwellings

In table 2.3, the total number of standardized descriptors is indicated for each of the above three test types. A requirement may be expressed as the sum of a single-number quantity and a spectrum adaptation term or solely as the single-number quantity. Examples of airborne and impact sound insulation requirements could be:

$$D_{nT,w} \geq 55 \text{ dB}; \qquad L'_{nT,w} \leq 50 \text{ dB};$$
$$D_{nT,w} + C \geq 55 \text{ dB}; \qquad L'_{nT,w} + C_I \leq 50 \text{ dB};$$
$$D_{nT,w} + C_{50\text{-}3150} \geq 55 \text{ dB}; \qquad L'_{nT,w} + C_{I,50\text{-}2500} \leq 50 \text{ dB};$$

Table 2.2. *Relevant spectrum adaptation term for different types of noise sources.*

Type of noise source	Relevant spectrum adaptation term
• Living activities (talking, music, radio, tv) • Children playing • Railway traffic at medium and high speed • Highway road traffic > 80 km/h (1) • Jet aircraft short distance • Factories emitting mainly medium and high frequency noise	C (Spectrum 1: A-weighted pink noise)
• Urban road traffic • Railway traffic at low speeds (1) • Aircraft propeller driven • Jet aircraft large distance • Disco music • Factories emitting mainly low and medium-frequency noise	C_{tr} (Spectrum 2: A-weighted urban traffic noise)
• ISO tapping machine	C_I

Ref.: ISO 717-1:2013 and ISO 717-2: 2013. The spectra 1 and 2 are defined in ISO 717-1.

The issue of descriptors is further elaborated in [7] and [13]. For some types of buildings, e.g. for light-weight buildings, it is important to include low-frequency spectrum adaptation terms or other criteria taking into account low frequencies, see e.g. references in [6-7] and results presented in the other chapters in this book.

Table 2.3. *Overview ISO 717 descriptors for evaluation of sound insulation in buildings.*

<table>
<tr><th>ISO 717:2013 descriptors for evaluation of field sound insulation</th><th>Airborne sound insulation between rooms (ISO 717-1) (b)</th><th colspan="2">Airborne sound insulation of facades (a) (ISO 717-1) (b)</th><th>Impact sound insulation between rooms (ISO 717-2) (b)</th></tr>
<tr><td>Basic descriptors (single-number quantities)</td><td>R'_{w}
$D_{n,w}$
$D_{nT,w}$</td><td colspan="2">R'_{w}
$D_{n,w}$
$D_{nT,w}$</td><td>$L'_{n,w}$
$L'_{nT,w}$</td></tr>
<tr><td rowspan="2">Spectrum adaptation terms (listed according to intended main applications)</td><td rowspan="2">None
C
$C_{50-3150}$
$C_{100-5000}$
$C_{50-5000}$</td><td colspan="2">None</td><td rowspan="2">None
C_{I}
$C_{I,50-2500}$</td></tr>
<tr><td>C
$C_{50-3150}$
$C_{100-5000}$
$C_{50-5000}$</td><td>C_{tr}
$C_{tr,50-3150}$
$C_{tr,100-5000}$
$C_{tr,50-5000}$</td></tr>
<tr><td>Total number of descriptors</td><td>3 x 5 = 15</td><td colspan="2">3 x 9 = 27</td><td>2 x 3 = 6</td></tr>
</table>

Notes

(a) For facades, the complete indices for R'_{w} , $D_{n,w}$, $D_{nT,w}$ are found in ISO 717.

(b) For simplicity, only 1/3 octave quantities and C-terms are included in the table, although some countries allow 1/1 octave measurements for field check.

2.4. Sound insulation requirements in Europe

Comparative studies of descriptors and regulatory sound insulation requirements in in Europe are described and discussed in detail in [6-7] and [13]. Results from extension to 35 countries and updates are presented in [14] and in this chapter. The comparison reveals significant differences in descriptors and requirements for dwellings. For both airborne and impact sound insulation requirements, several descriptors are applied in Europe. Table 2.4 indicates how many countries apply the different descriptors and besides, there are variants; recommendations and special rules.

The standard EN ISO 717 from 1996 has contributed to the diversity in Europe by allowing many different descriptors and by introducing spectrum adaptation terms with different extended frequency ranges, and these are maintained in the most recent version from 2013 [11], see Tables 2.1 and 2.3.

Table 2.4. *Sound insulation descriptors applied for regulatory requirements in 30 countries Europe in June 2013.*

Airborne sound		Impact sound	
No. of countries	**Descriptor**	**No. of countries**	**Descriptor**
16	R'_{w}	18	$L'_{n,w}$
3	$R'_{w} + C$	1	$L'_{n,w} + C_{I,50\text{-}2500}$
1	$R'_{w} + C_{50\text{-}3150}$	8	$L'_{nT,w}$
6	$D_{nT,w}$	2	$L'_{nT,w} + C_{I}$
2	$D_{nT,w} + C$	1	L'_{w}
1	$D_{nT,A}$ ($\approx D_{nT,w} + C$)	?	Variants
1	$D_{nT,w} + C_{tr}$	?	Recommendations
?	Variants	?	Special rules
?	Recommendations		
?	Special rules		

The main requirements for airborne and impact sound insulation are presented in Tables 2.5 and 2.6. In order to facilitate a comparison between countries, all requirements have been converted into estimated equivalent values of $D_{nT,w}$ and $L'_{nT,w}$ based on assumptions about rooms and construction types, see Chapter 4, and the results for multi-storey housing are shown in Figures 2.2 and 2.3. The equivalent values are estimates only, as exact conversion is not possible. The results in Figures 2.2 and 2.3 show large differences between countries, especially for impact sound insulation requirements with max differences of equivalent $L'_{nT,w}$ limits more than 15 dB for multi-storey housing.

When digging deeper into the building codes and related documents, hidden special rules and/or conditions are often revealed. For example, see [15], the Swiss standard SIA 181:2006 with sound insulation requirements have become very complex to apply due to several nuisance levels and receiver sensitivity levels. Furthermore, national methods, procedures and correction terms have been defined. The symbol table is 11 pages! Another example can be special rules found in the Nordic countries, see [16-17]. Even in case of seemingly identical limits, sometimes they are different due to special rules, e.g. volume limitations.

The main findings from the comparison of regulatory airborne and impact sound insulation requirements are found in Table 2.7.

Table 2.5. *Airborne sound insulation between dwellings - Main requirements in 35 European countries[1].*

Status June 2013[1]		Multi-storey housing	Row housing
Country [10]	Descriptor [2]	Req. [dB]	Req. [dB]
Austria	$D_{nT,w}$	≥ 55	≥ 60
Belgium	$D_{nT,w}$	≥ 54	≥ 58
Bulgaria	R'_{w}	≥ 53	≥ 53
Croatia	R'_{w}	≥ 52	≥ 52
Cyprus (8)	N/A	N/A	N/A
Czech Rep.	R'_{w}	≥ 53	≥ 57
Denmark	R'_{w}	≥ 55	≥ 55
England & Wales	$D_{nT,w} + C_{tr}$	≥ 45	≥ 45
Estonia	R'_{w}	≥ 55	≥ 55
Finland	R'_{w}	≥ 55	≥ 55
France	$D_{nT,w} + C$	≥ 53	≥ 53
Germany	R'_{w}	≥ 53 (4)	≥ 57
Greece (9)	R'_{w}	≥ (50)	≥ (50)
Hungary	$R'_{w} + C$	≥ 51	≥ 56
Iceland	R'_{w}	≥ 55	≥ 55
Ireland	$D_{nT,w}$	≥ 53 (4)	≥ 53
Italy	R'_{w}	≥ 50	≥ 50
Latvia	R'_{w}	≥ 54	≥ 54
Lithuania	$D_{nT,w}$ or R'_{w}	≥ 55	≥ 55
Luxembourg (8)	N/A	N/A	N/A
Macedonia FYR (8)	N/A	N/A	N/A
Malta (8)	N/A	N/A	N/A
Netherlands	$R'_{w} + C$	≥ 52	≥ 52
Norway	R'_{w} (3)	≥ 55 (3)	≥ 55 (3)
Poland	$R'_{w} + C$	≥ 50 (4)	≥ 52 (5)
Portugal	$D_{nT,w}$	≥ 50	≥ 50
Romania (6)	R'_{w}	≥ 51	≥ 51
Scotland	$D_{nT,w}$	≥ 56	≥ 56
Serbia	R'_{w}	≥ 52	≥ 52
Slovakia	R'_{w} or $D_{nT,w}$	≥ 53	≥ 57
Slovenia	R'_{w}	≥ 52	≥ 52
Spain	$D_{nT,A} \approx D_{nT,w} + C$	≥ 50	≥ 50
Sweden	$R'_{w} + C_{50\text{-}3150}$	≥ 53	≥ 53
Switzerland	$D_{nT,w} + C$	≥ 52 (7)	≥ 55
Turkey (8)	N/A	N/A	N/A

Table 2.6. *Impact sound insulation between dwellings - Main requirements in 35 European countries[(1)].*

Status June 2013[(1)]		Multi-storey housing	Row housing
Country [(11)]	**Descriptor [(2)]**	**Req. [dB]**	**Req. [dB]**
Austria	$L'_{nT,w}$	≤ 48	≤ 43
Belgium	$L'_{nT,w}$	≤ 58 (3)	≤ 50
Bulgaria	$L'_{n,w}$	≤ 53	≤ 53
Croatia	L'_{w} (5)	≤ 68	≤ 68
Cyprus (9)	N/A	N/A	N/A
Czech Rep.	$L'_{n,w}$	≤ 55	≤ 48
Denmark	$L'_{n,w}$	≤ 53	≤ 53
England & Wales	$L'_{nT,w}$	≤ 62	None
Estonia	$L'_{n,w}$	≤ 53	≤ 53
Finland	$L'_{n,w}$ (4)	≤ 53 (4)	≤ 53 (4)
France	$L'_{nT,w}$	≤ 58	≤ 58
Germany	$L'_{n,w}$	≤ 53	≤ 48
Greece (10)	$L'_{n,w}$	≤ (60)	≤ (60) 60 info
Hungary	$L'_{n,w}$	≤ 55	≤ 45
Iceland	$L'_{n,w}$	≤ 53	≤ 53
Ireland	$L'_{nT,w}$	≤ 62	None
Italy	$L'_{n,w}$	≤ 63	≤ 63
Latvia	$L'_{n,w}$	≤ 54	≤ 54
Lithuania	$L'_{n,w}$	≤ 53	≤ 53
Luxembourg (9)	N/A	N/A	N/A
Macedonia FYR (9)	N/A	N/A	N/A
Malta (9)	N/A	N/A	N/A
Netherlands	$L'_{nT,w} + C_I$	≤ 54	≤ 54
Norway	$L'_{n,w}$ (4)	≤ 53 (4)	≤ 53 (4)
Poland	$L'_{n,w}$	≤ 58	≤ 53
Portugal	$L'_{nT,w}$	≤ 60	≤ 60
Romania (7)	$L'_{n,w}$	≤ 59	≤ 59
Scotland	$L'_{nT,w}$	≤ 56	None
Serbia	$L'_{n,w}$	≤ 68	≤ 68
Slovakia	$L'_{n,w}$ or $L'_{nT,w}$	≤ 55	≤ 48
Slovenia	$L'_{n,w}$	≤ 58	≤ 58
Spain	$L'_{nT,w}$	≤ 65	≤ 65
Sweden	$L'_{n,w} + C_{I,50\text{-}2500}$	≤ 56 (6	≤ 56 (6)
Switzerland	$L'_{nT,w} + C_I$	≤ 53 (8)	≤ 50
Turkey (9)	N/A	N/A	N/A

Notes to table 2.5

(1) Overview information only. Detailed requirements and conditions are found in the building codes. All data to be verified/corrected in 2014. The original study for 24 countries is from 2008. Bulgaria, Croatia, Cyprus, Greece, Luxembourg, Macedonia FYR, Malta, Romania, Scotland, Serbia, Turkey are new countries added in March 2011. CZ, IS, PT have been updated 2011 due to revision of building codes. In 2013, Greece has been added; Iceland and Slovakia updated.
(2) No generally applicable conversion between the different descriptors exists, as the relations depend on characteristics of rooms and constructions. Exact conversion can only be made in specific cases.
(3) Recommended that the same criteria are fulfilled by $R'_w + C_{50\text{-}5000}$.
(4) Horizontal, requirement for vertical is 1 dB higher (Bulgaria, Germany, Poland) / lower (Ireland).
(5) 55 dB recommended.
(6) Under revision.
(7) Flats for rent. If owned by occupants, same limit as for row housing.
(8) No regulatory requirements. In Luxembourg, most often limits from Belgium or other neighbouring countries are applied, dependant on the consultant. In Turkey, requirements in preparation.
(9) Proposed requirements, not yet mandatory.
(10) Although England & Wales and Scotland are parts of UK, they are listed as separate countries due to different requirements.

Notes to table 2.6

(1) Overview information only. Detailed requirements and conditions are found in the building codes. All data to be verified/corrected in 2014. The original study for 24 countries is from 2008. Bulgaria, Croatia, Cyprus, Greece, Luxembourg, Macedonia FYR, Malta, Romania, Scotland, Serbia, Turkey are new countries added in March 2011. CZ, IS, PT have been updated 2011 due to revision of building codes. In 2013, Greece has been added; Iceland and Slovakia updated.
(2) No generally applicable conversion between the different descriptors exists, as the relations depend on characteristics of rooms and constructions. Exact conversion can only be made in specific cases.
(3) From "non-bedrooms" outside the dwelling to a bedroom ≤ 54 dB is required.
(4) Recommended that the same criteria are fulfilled by $L'_{n,w} + C_{I,50\text{-}2500}$.
(5) L'_w not defined in ISO 717-2. It is assumed to be $L'_{n,w}$.
(6) The same criteria shall also be fulfilled by $L'_{n,w}$.
(7) Under revision.
(8) Flats for rent. If owned by occupants, same limit as for row housing.
(9) No regulatory requirements. In Luxembourg, most often limits from Belgium or other neighbouring countries are applied, dependant on the consultant. In Turkey, requirements in preparation.
(10) Proposed requirements, not yet mandatory.
(11) Although England & Wales and Scotland are parts of UK, they are listed as separate countries due to different requirements.

Table 2.7. *Main findings from comparison of requirements in 35 countries in Europe, 2013.*

Airborne sound insulation	Impact sound insulation
• 7 descriptors + variants/ recommendations • For multi-storey housing differences up to 6 dB • For row housing differences up to 10 dB • 8 countries apply C-terms • Low-frequency C-terms applied only in Sweden • The strictest requirements for are found in Scotland and Austria for multi-storey and row housing, respectively • 5 countries have no requirements	• 5 descriptors + variants/ recommendations • For multi-storey housing max difference > 15 dB • For row housing max difference > 20 dB • 3 countries apply C-terms • Low-frequency C-terms applied only in Sweden • The strictest requirements are found in Austria for both for multi-storey and row housing • 5 countries have no requirements

In regulatory terms, a significant challenge is that for some types of light-weight constructions, the subjective sound insulation is ranked lower than for a heavy construction with the same objective sound insulation. Regulatory requirements are objective, and the same requirements should be applicable for all types of housing constructions and materials. Thus, an important research task is to develop new objective descriptors (evaluation methods) correlating with the subjective evaluation for all types of constructions. – In Norway, a survey [18] about satisfaction with newly built homes (2005) has been carried out in 2007. In general, people are satisfied (about 80%, 10% dissatisfied). Least satisfaction (17% dissatisfied) is found with sound insulation, especially for 2-storey housing (27% dissatisfied). According to [19], the reason is likely to be light-weight constructions applied for such housing.

Requirements for facade sound insulation

This paper focuses on sound insulation between dwellings, and only general principles for facade sound insulation requirements will be dealt with. As shown in Table 2.3, there are 27 facade sound insulation descriptors based on ISO 717 [11]. However, regulatory requirements for facade sound insulation can be expressed in more ways, directly or indirectly:

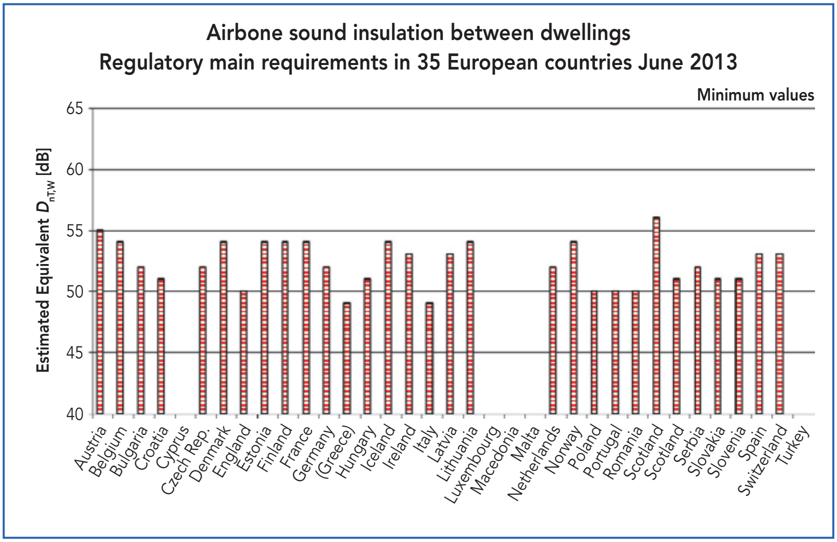

Figure 2.2. *Overview of airborne sound insulation requirements between dwellings. Graphical presentation of estimated equivalent values of $D_{nT,w}$. Note: The equivalent values are estimates only, as exact conversion is not possible, see Ch. 4.*

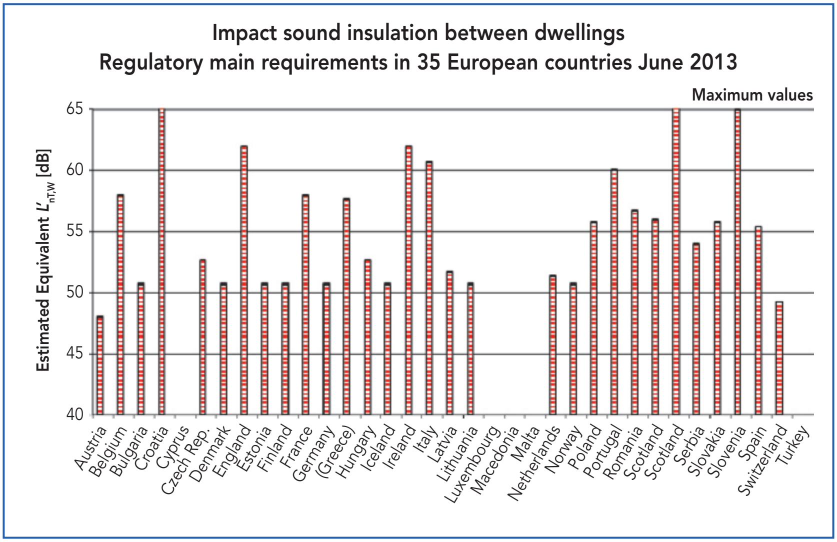

Figure 2.3. *Overview of impact sound insulation requirements between dwellings. Graphical presentation of estimated equivalent values of $L'_{nT,w}$. Note: The equivalent values are estimates only, as exact conversion is not possible, see Ch. 4.*

- Minimum facade sound insulation as a function of outdoor noise level (e.g. FR, DE, LT, NL, AT)
- Max indoor noise levels (e.g. DK, FIN, IS, NO, SE)
- Max "night event" levels - combined with other criteria (e.g. NO, SE)

Consequently, descriptors related to regulations for sound insulation against traffic noise are not always defined in ISO 717. Nevertheless, all methods lead to sound insulation requirements for the facade components. The required sound insulation depends on the outdoor noise level and maximum indoor level. The outdoor noise levels are calculated based on the traffic data and conditions. Often, the traffic noise levels are available from authorities. The levels vary with location, see Figure 2.4.

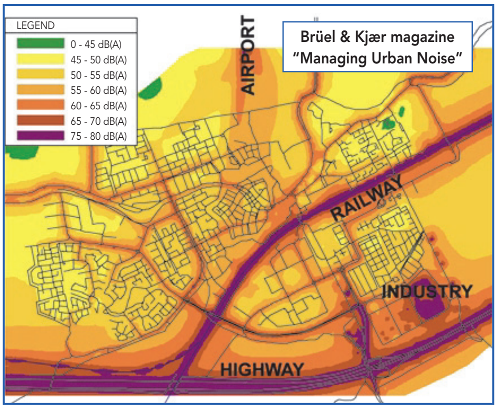

Figure 2.4. *Example of mapping of outdoor noise from road traffic, railways, airports and industry. The regulatory sound insulation requirement for facades depends on the outdoor level and thus of the location.*

Figure 2.5 shows housing facing a busy road. The housing blocks behind those facing the road are less exposed to traffic noise, and thus requirements could be less strict.

Noise mapping and action plans are mandatory according to the European Environmental Noise Directive (END), [20]. A strategy for a quieter Europe is presented in [21]. In several countries, facade sound insulation requirements are specified as a function of the outdoor traffic noise levels calculated according to other methods than defined in the END [20], and in some countries there are additional limits for night events. When reviewing such limits, the WHO night noise guidelines in [22] might be useful.

Figure 2.5. *Housing block facing a busy road.*

Like requirements for sound insulation between dwellings, the situation seems quite chaotic, when trying to exchange experience between countries.

2.5. Sound classification schemes in Europe

Sound classification schemes describe different quality classes to meet different needs of activities and quietness in the home. In this chapter a classification scheme is understood as a set of minimum 3 classes with different sound insulation performance levels. Using this definition, classification schemes for dwellings exist at present in 10 countries in Europe [23-32]. In Germany, an additional recommendation [33] has been prepared. The first classification schemes for dwellings were implemented in the early 1990s. Sound classification schemes in Europe are national schemes, the majority being published by national standardization organizations, see Figure 2.6. An overview of existing sound classification schemes for dwellings [23-32] is found in Table 2.8. For each scheme, information is found about class denotations, relation to the national building code and the classes intended for new and for existing (old/ renovated and other not new) housing, respectively. The schemes specify class criteria concerning several acoustic aspects. The schemes and main class criteria are described in more detail in [8-9], for facades in [34, 36]. Aspects related to sound classes for renovated housing are described in [35]. More schemes are under development in other countries, unfortunately different from and not coordinated with update of other schemes in Europe.

The different classes in the classification schemes are intended to reflect different levels of acoustical comfort. Thus, to be able to make a qualified choice of sound class, it is of course relevant to know the degree of acoustical comfort or occupants' satisfaction for the respective classes. For this reason, it has been found important to include such indications in the TU0901 proposal for a classification scheme, see Chapter 5.

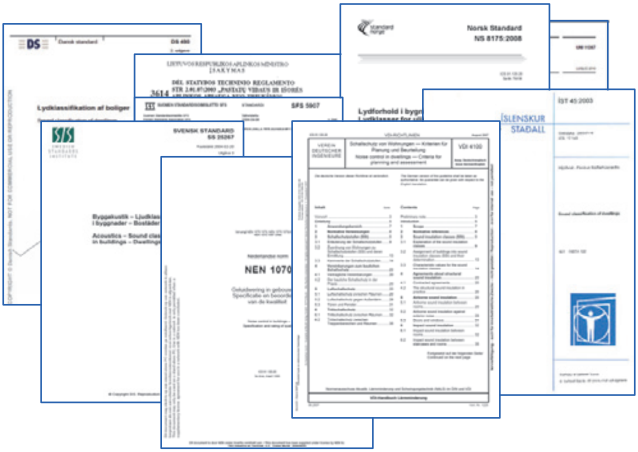

Figure 2.6. Most classification schemes in Europe are published by national standardization organizations. Only in Germany, the scheme is published by "private" organizations. An overview of schemes is found in Table 8.

Table 2.8. European schemes for sound classification of dwellings, relation to building codes and indication of classes intended for new and "old" dwellings. Status June 2013.

Country	Class denotations[1]	CS Reference (latest version)	Link BC to CS	BC Reference to CS	Comment	Classes for new dwellings	Classes for "old" dwellings
DK	A / B / C / D	DS 490 (2007)	+	Class C		A, B, C	D
FI	A / B / C / D	SFS 5907 (2004)	–	N/A	BC = Class C	A, B, C	D
IS	A / B / C / D	IST 45 (2011)	+	Class C		A, B, C	D
NO	A / B / C / D	NS 8175 (2012)	+	Class C		A, B, C	D
SE	A / B / C / D	SS 25267 (2004)	+	Class C		A, B, C	D
LT	A / B / C / D / E	STR 2.01.07 (2003)	+	Class C		A, B, C	D, E
IT	I / II / III / IV	UNI 11367 (2010)	–	N/A	BC ~ Class III	I / II / III / IV	
DE [2]	III / II / I	VDI 4100 (2012) [3]	–	N/A		III, II, I	None
AT	A / B / C / D / E	ÖNORM B 8115-5 (2012)	–	N/A	BC = Class C	A, B, C	D, E
NL	I / II / III / IV / V	NEN 1070 (1999)	–	N/A	BC ~ Class III	I / II / III	IV, V
"TU0901"	A – F and npd	TU0901 Conf.Book (2013)	N/A	N/A	(4)	A / B / C / D / E / F and npd	

Abbreviations: BC = Building Code (regulatory requirements); CS = Classification scheme

(1) Classes are indicated in descending order, i.e. the best class first.

(2) Moreover, the German Society of Acoustics (DEGA) has published a recommendation [17] for acoustic labelling of dwellings. The system has seven classes A*-F and a colour code, the lower classes intended for old buildings.

(3) The revised version of VDI 4100 published in 2012 changed descriptors from R'_w and $L'_{n,w}$ to $D_{nT,w}$ and $L'_{nT,}$ as had been discussed for years for the regulations. Also the class criteria were made stricter, and all classes are now above regulation (before the lowest class corresponded to regulations).

(4) Proposal prepared by TU0901, see Ch. 5. Considered to be submitted as WIs for international standardization.

Comparing the data from the 10 classification schemes in Europe, see Table 2.8, Figures 2.7-2.8 and detailed class criteria in [9], several differences are found:

- Number of quality classes (3 to 5) and denotations (see table 2.8)
- Range of quality classes (8-20 dB for airborne, 14-20 dB for impact) and position
- Intervals between classes (3-6 dB for airborne, 2-10 dB for impact)
- Descriptors used for sound insulation criteria
- Use of low-frequency spectrum adaptation terms according to ISO 717:2013 [11]
- Common or separate quality levels for multi-storey and row housing
- Relation to regulatory requirements

The majority of the classification schemes include criteria for sound insulation internally in dwellings, see [8, 36] and [23-32].

The most striking differences between countries and between classes are found in impact sound criteria, e.g. the best class in [30] corresponds approximately to the lowest class in [31] and [32], see Figure 2.8 and [9].

When comparing the information in Table 2.8, some schemes may appear similar, eg NL and IT, but they are very different. Even the Nordic schemes are more different than they appear from Table 2.8, see [36].

Based on a comparison of the existing schemes, it seems as if a European proposal could be a scheme having 4 or 5 classes with about 4 dB intervals between airborne classes and about 5 dB intervals between impact classes. A key issue is whether low-frequency rating should be included in all classes or maybe only the upper classes. Results of discussions are found in the scheme presented in Ch. 5.

2.6. Is harmonization of sound insulation descriptors and classes possible?

Looking into the future, harmonization of sound insulation requirements seems unrealistic. However, by reducing the number of sound insulation descriptors and by preparing a harmonized European classification scheme with a number of quality classes, each member state could select for regulations a "harmonized" class fitting the national needs and conditions. Having said that, it must be emphasized that there are big jungles to be removed, before "transparent" limits can be implemented.

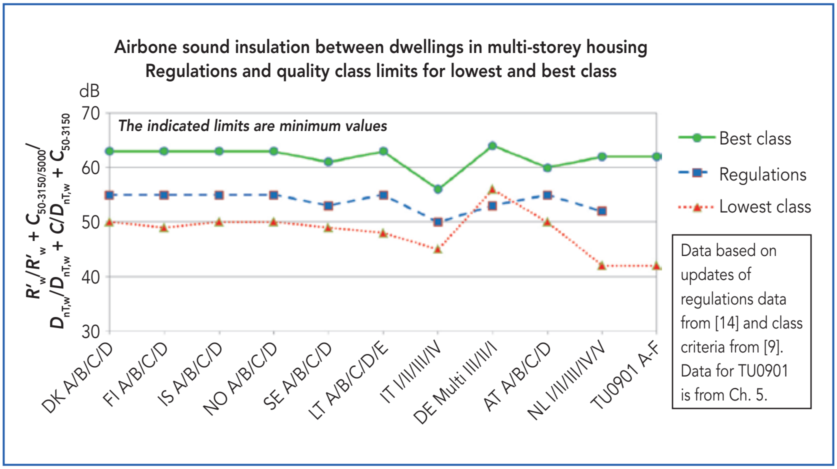

Figure 2.7. *Airborne sound insulation limits for highest and lowest classes in 10 classification schemes in Europe and regulatory requirements for the same countries. TU0901 class limits for highest and lowest class shown in the right side for comparison. Note: The diversity of descriptors appears from the Y-axis label. The graphs present the numbers only. No conversions between descriptors have been applied.*

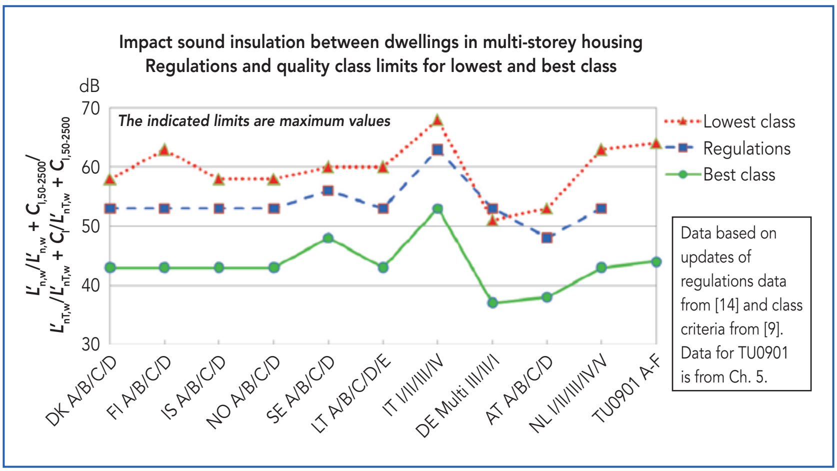

Figure 2.8. *Impact sound insulation limits for highest and lowest classes in 10 classification schemes in Europe and regulatory requirements for the same countries. TU0901 class limits for highest and lowest class shown in the right side for comparison. Note: The diversity of descriptors appears from the Y-axis label. The graphs present the numbers only. No conversions between descriptors have been applied.*

Jungles to be removed – Replanting forbidden!

Jungle 1: The variety of standardized sound insulation descriptors, see EN ISO 717 [11].

Jungle 2: Complex national rules making it difficult to find the limit values, see [15].

Jungle 3: National special rules in addition to standardized methods, see [16, 17].

Implementation and enforcement of sound insulation requirements

Important tasks and tools for upgrading sound insulation requirements and to make an efficient and effective implementation in practice are:

- Review of national requirements and upgrade, if needed
- Construction databases and guidelines for improvement of existing housing
- Construction databases and guidelines for new housing
- Enforcement of regulations
- Feedback from field testing

Examples of guidelines and enforcement

Examples of instructions for improvement of existing/old housing are found in Figure 2.9. For new buildings, "Robust Details" [37] implemented in UK is an example of a coordinated approach, including construction design, acoustic site inspection, checklists, field testing and systematic feedback to the design and performance review. In practice, Robust Details supports enforcement. Examples of construction details and checklists are shown in Figure 2.10.

It seems as if all the necessary tools and experience exist to get the change process and implementation started. When a single national committee struggles on its own, the full process would typically take 10-20 years or even more – or never happen. However, by using the network established through COST TU0901, exchange of experience has already started, and the process and implementation could run much more effectively and efficiently.

There are of course still research needs, but these could be defined now on a better ground and joint projects could be applied for and thus prepare the ground for continued innovation, exchange of experience and dissemination of findings.

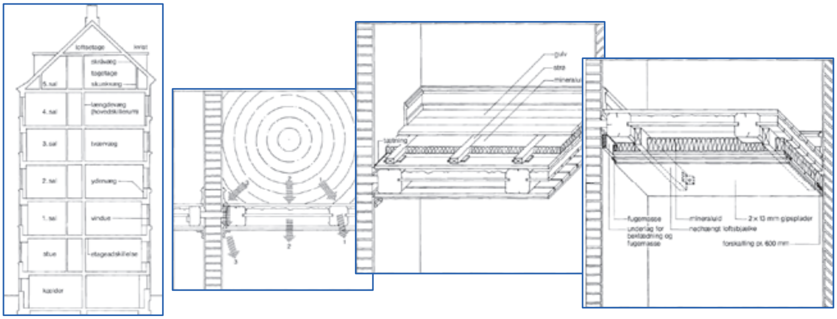

Figure 2.9. *Examples on instructions for improvement of sound insulation of old housing. Source: SBi Guidelines 173, Sound insulation of buildings – Old buildings, 1992 (in Danish).*

According to [38], the coordinated approach in Robust Details [37] "can lead to an accelerated uptake in improved construction practice and allow government policy performance objectives to be met sooner". Thus, there is a high potential.

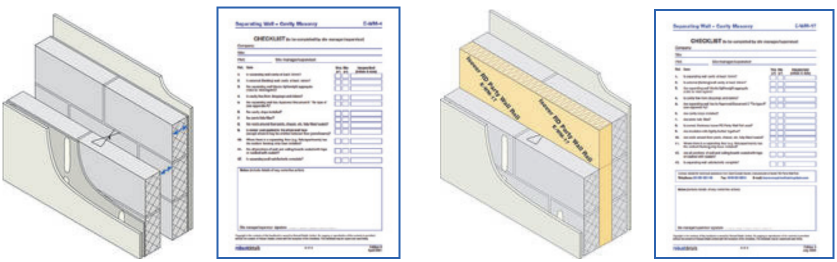

Figure 2.10. *Examples construction details and related checklists from Robust Details [37].*

2.7. Conclusions and acknowledgements

Most European countries have regulatory sound insulation requirements for dwellings, and classification schemes exist in several countries. However, both descriptors, requirements and class criteria present a high degree of diversity. Unfortunately, there is no sign of increasing harmonization, rather the contrary, i.e. evidence for an even more diverse situation in Europe. The studies conclude that harmonization of descriptors and sound insulation classes is needed to facilitate exchange of data and experience between countries, thus improving chances of better quality of dwellings, to stimulate innovation and to reduce trade barriers. Most important is, however, that review and update/upgrade of sound insulation requirements should be initiated in several countries to adapt regulations to current construction trends and peoples' needs for health, wellbeing and comfort.

The authors - Chair and Vice Chair of TU0901 – are grateful to all those enthusiastic people from many countries being active in TU0901: The WG leaders, the MC and WG members, in total nearly 100 people from 29 countries in Europe and three overseas countries. In addition: Thanks to COST Office for support.

COST TU0901 has – through members with different academic backgrounds (architects, physicists, civil engineers etc.) and from different types of institutions (universities, building research institutes, authorities, private companies etc.) – the potential to establish a change process in a direction ensuring strengthened scientific basis for changes in sound insulation descriptors, requirements and classes. - We eagerly anticipate collaborative developments in this field.

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3

Proposal of Harmonized Sound Insulation Descriptors

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CHAPTER 3 Proposal of Harmonized Sound Insulation Descriptors

3.1. Introduction

Currently many different descriptors are used in the various countries to express the acoustic performance of buildings. COST TU0901-working group 1 started with the collection of all feasible descriptors for the acoustic performance of buildings: airborne sound insulation, impact sound insulation, façade sound insulation and sound levels due to service equipment (see chapter 2). The advantages and disadvantages for each of these were collected, grouped and discussed.

During a discussion over these results in May 2011 a first proposal was drafted for the most appropriate descriptors and assessment methods. These proposals were than summarized after a second round of comments and discussion at the meeting in Dübendorf/Zürich in November 2011. Finally, after voting on the high end of the frequency range, the proposal was reviewed and finalized at the meeting in Prague in June 2012. This was then the basis for further work on the classification scheme.

Between that moment and the end of the action the proposed frequency range, 50 to 5000 Hz, was the subject of lively debate both within and outside the Action, as within standardization bodies (ISO, CEN).

The high frequency range extension was considered impractical, mainly due to background noise problems, and was not considered essential, leading to the clear preference to keep the 'old' limits of 3150 Hz and 2500 Hz.

The need for the low frequency end, at least for airborne and façade sound insulation, was doubted for many constructions and found too impractical for many situations, leading to an acceptance of both 50 Hz and 100 Hz as options for the start of the frequency range. This has now been incorporated in the proposal for descriptors.

The final proposals for descriptors are presented in the following sections for each aspect with the advantages and reasoning for the proposed quantity, frequency range and assessment method in each case. Additional comments are provided on the need for adjustments in quantities and improvements in measurement methods, especially for lower frequencies. Similar needs were identified in relation to prediction methods.

Finally, the proposed descriptors are summarised in the conclusions to this chapter.

3.2. Airborne sound insulation

Preferred quantity: D_{nT}

- Good relation to the subjective estimation of insulation.
- Long experience and data available.
- No need to determine room volume or area of separating element.
- Simple to explain and easy to use.

Preferred frequency range: 1/3-octave bands 50 or 100 to 3150 Hz

- The measurement up to 3150 Hz correspond to the current practice and are sufficient to characterise the performance.
- Measurements below 50 Hz are not necessary except for very specialised applications.
- The performance between 50 and 100 Hz is important for lightweight buildings and some resonant building constructions.

Preferred assessment method: appropriate source spectrum and A-weighting

- Gives a better description of the real situation than curve shifting.
- Assessment is easy to explain and easy to calculate.

However:

- The reproducibility of measurements at low frequencies should be improved.

3.3. Impact sound insulation

Preferred quantity: L'_{nT}

- Good relation to the subjective estimation of insulation.
- Long experience and data available.
- No need to determine room volume.
- Simple to explain and easy to use.

Preferred frequency range: 1/3-octave bands 50 or 100 to 2500/3150 Hz

- The measurement up to 3150 or 2500 Hz correspond to the current practice and are sufficient to characterise the performance of the structure as is.
- Measurements below 50 Hz are not necessary except for very specialised applications, and perhaps very lightweight structures (more research is needed).
- The performance between 50 and 100 Hz is essential for lightweight constructions, useful with floating floors.

Preferred assessment method: Source transfer with A-weighting for relevant sources

- Source transfer (walking) and A-weighting (like $L'_{nTw}+C_I$) has emphasis on low frequencies as this is more relevant for subjective assessment, at least for 'heavy/soft' impact sources.
- A second criterion may be needed to represent higher frequency sources on masonry and concrete; for this a comparable type of weighting could be developed to provide a rating closely correlated with the current L'_{nTw}.

However:

- The reproducibility of measurements at low frequencies should be improved.
- It would be beneficial to have a more coherent system, assessing low frequency walking and higher frequency impacts in the same way, i.e. an appropriate combination of the weighting in $L'_{nTw}+C_I$ and L'_{nTw}.

3.4. Façade sound insulation

Preferred quantity: $D_{2m,nT}$

- Good correlation with occupants perception.
- Can also deal with complex façades.
- In some countries it is already used in Building Codes and/or land use planning.
- Using a loudspeaker increases reproducibility and simplifies the measurements (simultaneous measurement inside and outside are not required).

- For special situations the actual sources could be used, for example to verify the specified indoor level instead of qualifying the facade performance.

Preferred frequency range 1/3-octave bands 50 or 100 to 3150 Hz

- Down to 50 Hz seems to be reasonable to consider especially to address lightweight constructions and noise from heavyweight traffic.
- Below 50 Hz does not seem to be necessary for most sources.

Preferred assessment method appropriate source spectrum and A-weighting

- Appropriate spectrum mostly road traffic.
- Good and direct relation with indoor sound levels and their subjective assessment.

However:

- A solution is needed for measurements in narrow streets and sloped roofs and interference effects at low frequencies.
- The reproducibility of measurements at low frequencies should be improved.
- Special source spectra needed for special situations.

3.5. Sound levels due to service equipment

Preferred quantity $L_{eq,nT}$ or $L_{F,max,nT}$ depending on the type of equipment

- L_{eq}: heating/cooling; Ventilation; Boiler; various.
- L_{max}: lift, waste water, rubbish chute, water supply, garage doors, pumps, various.
- For relevant equipment L_{max} takes into account impulsive character.
- Normalization needed to cover both new and occupied dwellings, thus always octave band measurements.

Preferred frequency range: octave bands 63 - 8000 Hz

- For correct subjective assessment the frequency range should begin at 50 Hz, so the 63 Hz octave band.
- Considering frequencies below 50 Hz is normally not necessary.

- Frequency range should be the same for all type of equipments.
- The 8 kHz octave band would be the normal upper limit, but due to background noise higher frequencies a lower cut-off at the 4kHz octave band could be allowed, depending on type of equipment.

Preferred assessment method: A-weighted level (L_{eq} or L_{max})

- A-weighting is considered the procedure which exhibit best correlation with subjective assessment.
- C-weighting may be more appropriate for some equipment (boilers, rubbish chutes).

However:

- For L_{eq} the existing methodology for background noise correction should be improved.
- For L_{max} repeatability requires averaging over at least three working cycles.
- Direct A-weighted measurements will only be possible for global measurements due to the required normalization to reverberation time.

3.6. Conclusions

This proposal deals with the preferred quantities, the frequency range to be considered and the assessment method to obtain a single number rating. These will be the descriptors on which the further work for classifications schemes will be based. The proposal specifies the ultimate goal for these descriptors, while being aware that some aspects need further research before they can be practically realized and would require parallel changes in other documents.

Conversely, some changes may be easy and quick, such as using only quantities standardised to reverberation time, and others need some more experience, in particular the inclusion of lower frequencies. Whichever route is taken, the objectives identified in this Action and summarized below should be clear.

The main conclusions are:

- all quantities are overall quantities, standardised to reverberation time;

- all quantities consider the frequency range from 50 to 3150/2500 Hz, or 63-8000 Hz for equipment sound, as adequate as well as the range from 100 Hz upwards as being sufficient for many situations;
- the assessment of all quantities can be considered to be based on A-weighting of the received level, either directly (equipment) or for an appropriate source (walking) or a source spectrum (road, train or aircraft traffic, music, neighbours airborne sound);
- descriptors shall all be indicated by a single symbol, which is kept as 'legible' as possible to minimise confusion for the users like $D_{nT,Atr}$ and no longer as a sum like $D_{nT,w} + C_{tr}$.

Table 3.1. Overview of acoustic descriptors proposed by TU0901.

Aspect	Quantity	Frequency range	Assessment	Provisional notation single number
Airborne insulation	D_{nT}	50 – 3150 Hz or 100 – 3150 Hz	Apink	$D_{nT,50}$ and $D_{nT,100}$
Impact insulation	L'_{nT}	50 – 2500 Hz or 100 – 2500 Hz	Awalking and weighted or improved combined rating	$L'_{nT,50}$ and $L'_{nT,100}$
Façade insulation	$D_{2m,ls,nT}$	50 – 3150 Hz or 100 – 3150 Hz	Atraffic (or Apink)	$D_{2m,nT,50}$ and $D_{2m,nT,100}$
Service equipment levels	$L_{eq,nT}$ or $L_{F,max,nT}$	63 – 8000 Hz (octave)	A weighted	$L_{Aeq,nT}$ or $L_{AF,max,nT}$

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4

How to Translate Sound Insulation Descriptors and Requirements

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CHAPTER 4 How to Translate Sound Insulation Descriptors and Requirements

4.1. Introduction

There are currently a large number of different descriptors used in the countries participating in COST Action TU0901. If the new descriptors recommended by the Action are to be implemented, each country will need to be able to translate their current building regulation limits so that they can be used with the new descriptors recommended by this Action. This translation is treated in a theoretical/empirical way and a statistical way.

4.2. Theoretical translation

In principle the translation can be done in two steps:

1. Translate the used quantity into the proposed quantity, e.g. R' into D_{nT}
2. Translate the used assessment system into the proposed assessment system, e.g. $D_{nT,w}$ into $D_{nT,50}$ ($=D_{nT,w}+C_{50-5000}$)

For both steps some assumptions will need to be made. Further research, possibly specific to each country, could further refine these assumptions.

4.2.1. Translation of quantities

The theoretical relationships between various quantities can be deduced from basic building acoustic equations and definitions. These relationships can involve the geometry (volume, area, etc.) of the situation for which assumptions will have to be made (average values and variation). The relationships do not depend on frequency and therefore can be applied to different frequency ranges. The relationships hold for each frequency band and therefore for each type of single number rating.

The main quantities currently in use in Europe for regulatory requirements are:

- airborne: R'; D_{nT}
- impact: L_n ; L_{nT}
- façade: R'_{45} ; $R_{tr,s}$; $D_{2m,nT}$; $L_{Aeq,inside}$
- equipment: $L_{I,A}$; $L_{I,nT,A}$ with time weighting e.g., F or S.

The following relationships can be described for the descriptors:

$$D_{nT} = R' + 10\lg\frac{0.16V}{T_o S_s} \quad \text{[dB]} \tag{4.1}$$

$$L'_{nT} = L'_n - 10\lg\frac{0.16V}{T_o A_o} \quad \text{[dB]} \tag{4.2}$$

$$D_{2m,nT} = R' + \Delta L_{fs} + 10\lg\frac{0.16V}{T_o S_s} \quad \text{[dB]} \tag{4.3}$$

$$D_{2m,nT} = L_{den} + C_r - L_{den,inside} \quad \text{[dB]} \tag{4.4}$$

$$L_{I,nT,A} = L_{I,A} - 0\lg\frac{T}{T_o} \quad \text{[dB]} \tag{4.5}$$

For façade insulation, different measurement methods are applied resulting in the quantities R'_{45} or $R_{tr,s}$. According to EN 12354-3[1] the following relationships hold: $R' \approx R'_{45} - 1$ and $R' \approx R_{tr,s}$. According to the same standard, for deeper balconies ΔL_{fs} can be positive a few dB. Otherwise it can be set to about zero ± 1 dB.

However, other relationships are not as straightforward. The relation between $L_{den,inside}$ and other descriptors like $L_{Aeq,24h}$ depends on the type of outdoor noise. Some indications give $L_{den,inside} \approx L_{Aeq,24h}$ + 2 dB; for this and other noise levels, descriptors relations for different types of outdoor noise need to be specified.

For service equipment sound levels, the influence of the time averaging depends strongly on the type of equipment. For more or less constant levels it could be stated that $L_{Aeq} \approx L_{A,maxS}$, while for transient sounds $L_{A,maxF}$ could be equal to or about 5 dB higher than $L_{A,maxS}$. Also these relations could be made more specific.

4.2.2. Fundamental assumptions

Depending on the quantity to be determined, knowledge of the typical volume *V* and the typical volume/area ratio *V/S* may be required. With additional knowledge of the typical variation in these aspects, variations in the relationships can also be estimated. These values could be derived from existing databases of typical constructions in each country, leading to different values for different countries. Currently, only data from an Italian study[2] on façade insulation is available for this analysis. Using the findings of this study and taking the average values minus one standard deviation to stay on the safe side, results in V = 52,5 m^3 and V/S=2,5 m.

These values are also relevant for internal vertical sound insulation. A reasonable estimate of T in furnished rooms is 0,5 s, while in unfurnished situations 1,5 s is reasonable. This leads to:

$$
\begin{aligned}
&D_{nT} = R' - 1{,}0 \\
&L'_{nT} = L'_{n} - 2{,}3 \\
&D_{2m,nT} = R_{tr,s} - 1{,}0; \qquad D_{2m,nT} = R'_{45} - 2{,}0 \\
&L_{I,nT,A} = L_{I,A} - 5 \ \text{(not furnished) or} - 0 \ \text{(furnished)}
\end{aligned}
\qquad \text{[dB]} \tag{4.6}
$$

4.2.3. *Translations of weighting procedures and requirements*

The relationship between the various weighting systems must consider the different frequency ranges and evaluation procedures. The common frequency range for sound insulation is 100-3150 Hz (in some cases octave bands from 125 Hz to 2 kHz); while the new proposed range is 50-3150 Hz, but also allowing for 100-3150 Hz.

The two evaluation procedures are curve shifting (w-procedure) and A-weighted source spectra (A-procedure). There is no mathematical relation between all these variations. Relationships can only be based on experience and statistical evaluation of data. The result will be different for different types of constructions such as lightweight and heavyweight.

However, as far as the frequency range is concerned, the translation also depends on a choice. Should the minimum insulation requirements remain the same when the frequency range is extended, or should the requirements be adjusted for the extended frequency range so that the traditional built (heavy) dwellings that currently fulfil the requirements will also fulfil these new ones? Since the extension of the frequency range is mainly needed to adequately assess lightweight building systems and building systems with elements that show low frequency resonances, the latter choice is made here.

The most extensive study into relationships between rating systems has been reported by Scholl, Lang & Wittstock(3). The relevant relationships for heavy constructions that can be deduced from that study are summarised below.

$$\text{airborne: } C_{50-5000} = 5{,}2 - 0{,}12R_w \qquad \text{[dB]} \tag{4.7}$$

$$\text{impact: } C_{I,50-2500} = 24{,}0 - 0{,}46L_{n,w} \qquad \text{[dB]} \tag{4.8}$$

C-terms for the current frequency range will also need to be switched between weighting systems. Based on what is often mentioned in literature, the following assumptions were used

(4.9) $C = -1; \quad C_{tr} = -5; \quad C_I = -10$ [dB]

However, this assumption for impact sound did not seem to work correctly. Therefore, an older data set[(4)] of impact sound measurements was used to analyse various effects of frequency range and assessment method. The fifty-one floors considered in that data set included homogeneous, heavy floors with and without floor coverings, cement based floating floors, lightweight floating floors and two completely lightweight floor constructions. The differences between C_I and $C_{I,50\text{-}2500}$ with the values of $L_{n,w}$ are compared in Figure 4.1.

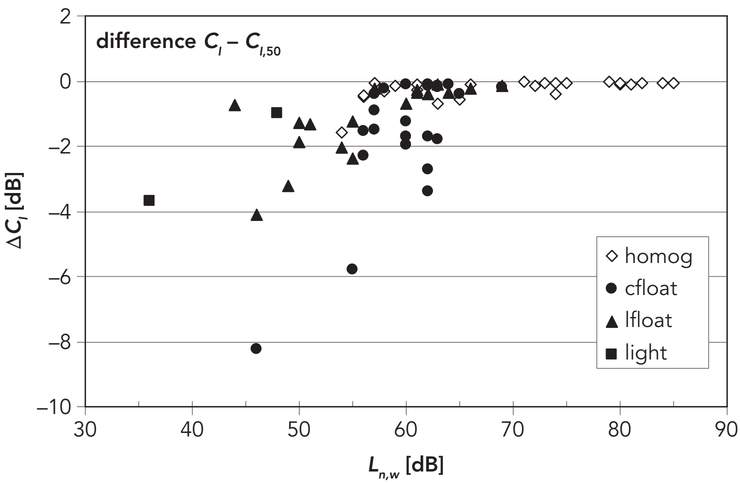

Figure 4.1. Difference between C_I and $C_{I,50\text{-}2500}$ for 51 floors as function of $L_{n,w}$; homog = homogeneous floors with and without floor covering; cfloat = cement type of floating floors; lfloat = lightweight floating floors and light= lightweight floor constructions.

For homogeneous floors, as well as for part of the floating floors, the difference in Figure 4.1 is very small. Therefore, to extend requirements expressed currently as $L_{n,w}+C_I$ to lower frequencies, the adjustment should be 0 dB; and there is no need to use a fixed value for C_I as in eq. (4.9).

Figure 4.2 compares the $C_{I,50\text{-}2500}$ for this data set with $L_{n,w}$ from Scholl *et al.*

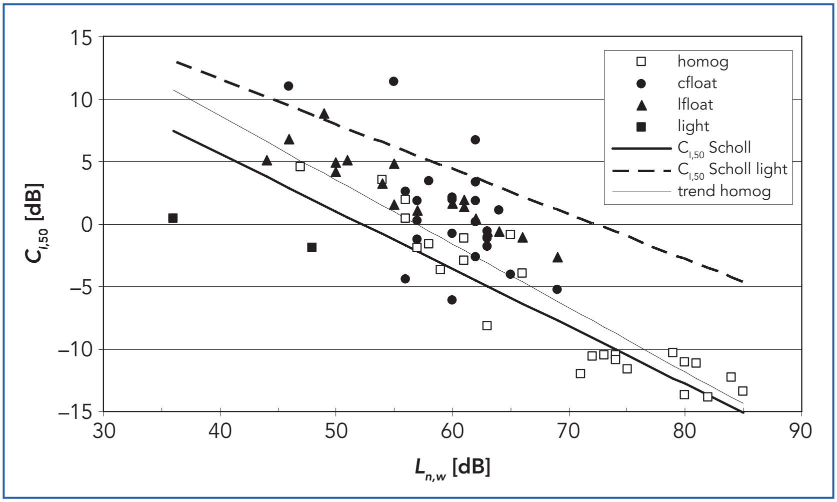

Figure 4.2. *$C_{I,50\text{-}2500}$ for 51 floors as function of $L_{n,w}$; legend as in Figure 4.1.*

For the homogeneous floors, the trend in Figure 4.2 corresponds reasonably to the results of Scholl e.g., while for all floors that trend is about 1 dB shifted. Therefore, it is proposed to use that trend for the translation instead of eq. (4.8) such that:

$$C_{I,50-2500} = 30{,}0 - 0{,}51 L_{n,w} \quad \text{[dB]} \tag{4.10}$$

In the studies used in this clause both field and laboratory data have been used, hence the dash in the quantities for field measurements has been omitted here. For the answers looked for, the relation between weighting procedures and frequency range, both types of data can be used as equivalent.

The translation for the façade descriptor could be based on the requirement that the resulting indoor level must be the same as before (explicitly or implicitly) when the lower frequencies down to 50 Hz are considered. If this is not the case in the current requirements, then those requirements are estimated to become about 2 dB more strict in that way.

4.2.4. Summary for the most common ratings

So in summary the theoretical/empirical translation of the requirements for airborne and impact sound can be done as follows.

The translation of the minimum requirements for airborne sound insulation starts from R'_w ; $D_{nT,w}$; $D_{nT,A100}$ (=$D_{nT,w}$+C) or $D_{nT,Atr100}$ (=$D_{nT,w}$+C_{tr}) as follows:

$$
(4.11)\quad
\begin{array}{ll}
R'_{w} \geq X: & D_{nT,50} \geq X - 1,0 + (5,2 - 0,12R'_{w}) \\
D_{nT,w} \geq X: & D_{nT,50} \geq X + 5,2 - 0,12(D_{nT,w} + 1,0) \\
D_{nT,A100} \geq X: & D_{nT,50} \geq X + 1 + 5,2 - 0,12(D_{nT,A100} + 2,0) \\
D_{nT,Atr100} \geq X: & D_{nT,50} \geq X + 5 + 5,2 - 0,12(D_{nT,Atr100} + 6,0)
\end{array}
\quad [\mathrm{dB}]
$$

And the translation for impact sound requirements starts from $L'_{n,w}$; $L'_{nT,w}$ or $L'_{nT,A100}$ ($=L'_{nT,w}+C_I$) as follows:

$$
(4.12)\quad
\begin{array}{ll}
L'_{n,w} \leq X: & L'_{nT,50} \leq X - 2,3 + (30,0 - 0,51L'_{n,w}) \\
L'_{nT,w} \leq X: & L'_{nT,50} \leq X + 30,0 - 0,51(L'_{nT,w} + 2,3) \\
L'_{nT,A100} \leq X: & L'_{nT,50} \leq X
\end{array}
\quad [\mathrm{dB}]
$$

For impact sound, the quantity $L'_{nT,w}$ is kept for the time being until an improved proposal for $L'_{nT,50}$ can be agreed upon.

4.3. Statistical translation of the currently used descriptors into the proposed new descriptors

The objective is to establish the relationship between the existing descriptors and the new descriptors so that different countries can translate their existing limits into the new descriptors. The theoretical method for the translation as described in the prior sections was developed on the bases of some fairly sensible but rigid assumptions.

A short term scientific mission (STSM), was undertaken at Edinburgh Napier University, as part of the work of the TU0901 Action[(5)]. The STSM showed that there is no simple one to one translation of the descriptors in the real world. A theoretical translation at best gives an average value. In the real world there will be a spread of values that are possible. What that spread is, and how to deal with it, can be answered by statistical comparisons.

In order to provide an example this section looks first at the building regulation descriptors used in England, Wales and Northern Ireland. When translating into the new descriptors the 'Living' spectrum from ISO/ NP/ 16717 Part 1 has been used as the 'A' weighting (the 'Living' spectrum corresponds to the existing spectrum for $C_{50\text{-}3150\mathrm{Hz}}$). The STSM identified four cases of heavy walls for which the value of $D_{nT,\mathrm{Living}}$ was 55 dB as shown in Figure 4.3.

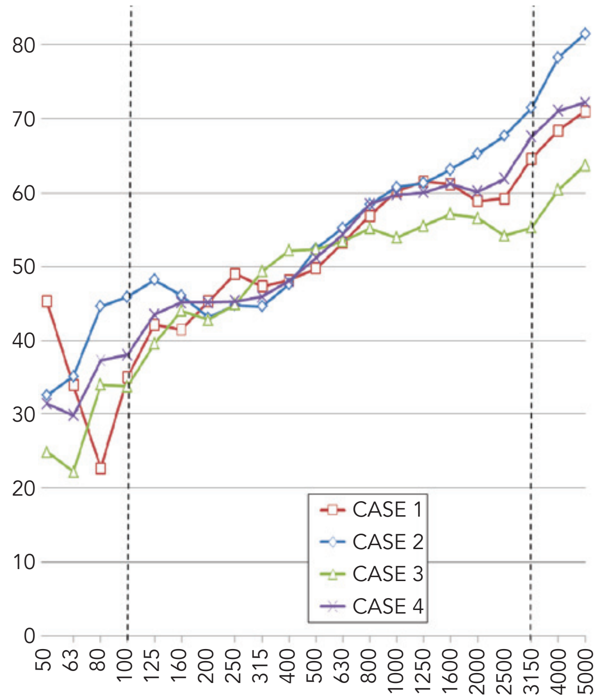

Figure 4.3. *Four spectra having the same value of single number quantity (SNQ):* $D_{nT,A\ 50–5000}$ *= dB.*

Each of the four walls shown in the figure has a very different spectral shape and therefore, each of the walls will be perceived by occupants as being different, though not necessarily as better or worse. The figure illustrates that when a weighting system is used to calculate a single number quantity it can have quite different spectral shape for the same SNQ value.

When these same spectra were converted to the single number quantity $D_{nT,w} + C_{tr}$ as per ISO 717 Part 1, the following values were found:

Case 1: 53 dB; Case 2: 52 dB; Case 3: 52 dB; Case 4: 51 dB

The reason that the $D_{nT,w} + C_{tr}$ value are different, even though the $D_{nT,A,50\text{-}5000}$ values were the same, is that ISO 717 Part 1 employs a different source spectrum and frequency range to calculate the single number quantities. For these four cases, the spread of the results is $D_{nT,w} + C_{tr}$ = 52 dB +/-1 dB.

One way of determining the range of translated values would be to use a 'Monte Carlo simulation' approach. The problem with that approach is that it would include many spectral shapes that could never occur in reality due to the nature of construction materials and methods. A better approach would be to analyse a large amount of field data and to plot the existing descriptor value against the new descriptor value for each construction as shown in Figure 4.4.

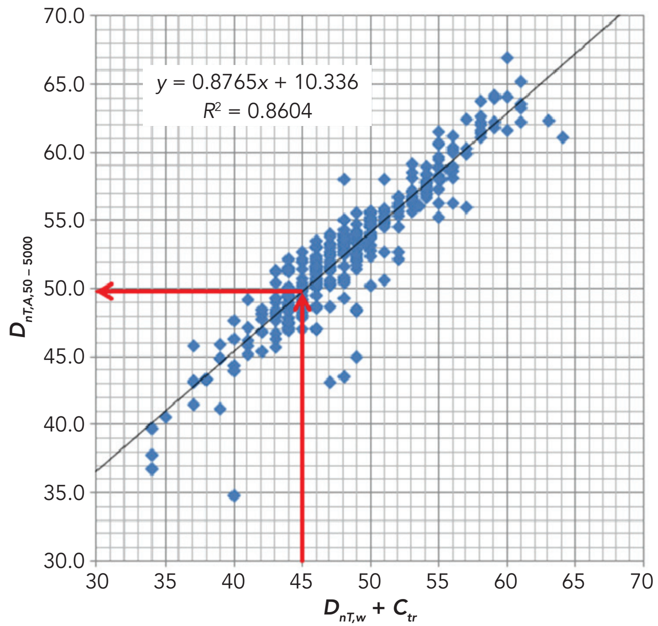

Figure 4.4. *$D_{nT,w} + C_{tr}$ plotted against the equivalent value of $D_{nT,A,50\text{-}5000}$. Graphical translation from old to new for England indicated.*

Figure 4.4 shows the relationship between the descriptors, $D_{nT,w} + C_{tr}$ and $D_{nT,A,50\text{--}5000}$ for a wide range of construction materials and methods.

In the English Building Regulations, the limit for airborne sound insulation between new build attached dwellings is 45 dB ($D_{nT,w} + C_{tr}$). In the figure it is shown that this limit is equivalent to a limit of 50 dB ($D_{nT,A,50\text{-}5000}$).

The theoretical calculation produced a value of 49,1 dB, which is in good agreement with the above graph which yields 49,8 dB for $D_{nT,A,50\text{-}5000}$. However, the general spread of results is quite large and is +/- 6dB as shown in Figure 4.5.

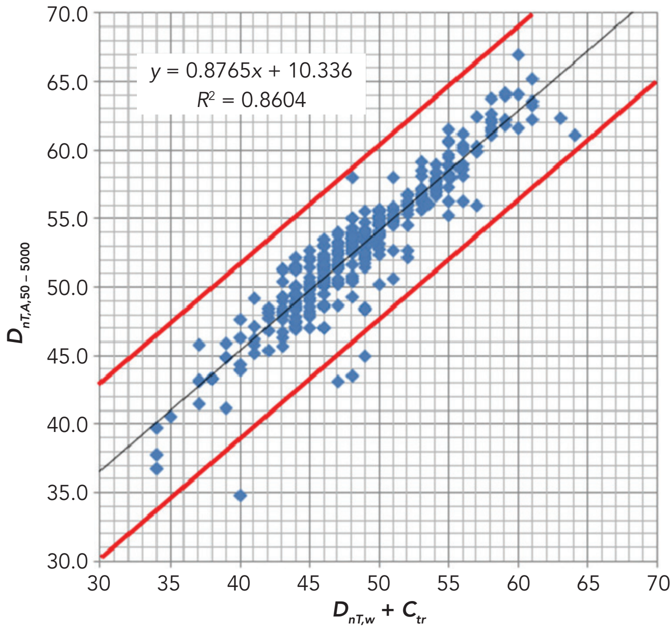

Figure 4.5. *Graphical translation from old to new descriptor with +/- 6 dB limits.*

The spread of values in the figure appears to be worse than it actually is. An analysis of only those tests which exactly achieved 45 dB ($D_{nT,w}$ + C_{tr}) shows the distribution pattern shown in Figure 4.6 when converted to the new $D_{nT,A,50\text{-}5000}$ descriptor for sixty three tests.

Ideally, the number of such tests would be increased to improve the assessment of the spread of results. However, based on the current set of data, the translation appears to be:

(4.13) $\quad$ 45 dB $D_{nT,w} + C_{tr}$ = 50 dB $D_{nT,A,50\text{-}5000}$ +/- 3dB

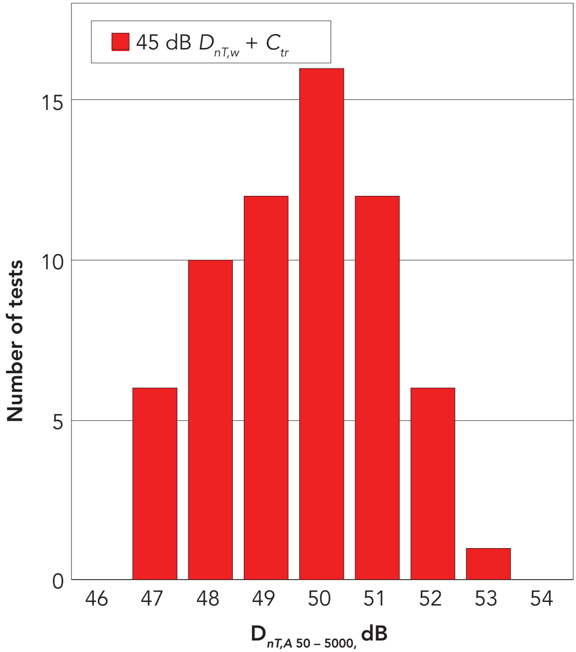

Figure 4.6. *Statistical distribution of all available tests that exactly measured 45 dB $D_{nT,w} + C_{tr}$.*

This approach to select a new limit can be adopted in each country based on the respective view of each government of whether they want to improve the current standard when the new limit is set. For example, in England a choice could be to accept the lower value of 47 dB $D_{\mathrm{nT,A,50\text{-}5000}}$ as the new limit. Figure 4.7 shows the implications of that decision.

Alternatively, if the higher value of 53 dB ($D_{\mathrm{nT,A,50\text{-}5000}}$) is chosen as the new limit, the implications of this choice are shown in Figure 4.8.

Whichever approach is adopted, there will be winners and losers. In practical terms, an increase of the limits is preferred and, therefore, it would be beneficial to adopt the upper limit of the translation.

4.3.1. The effect of partition construction

As in section 4.2, there is a question as to whether the partition construction type has any effect on the translation into the new descriptors.

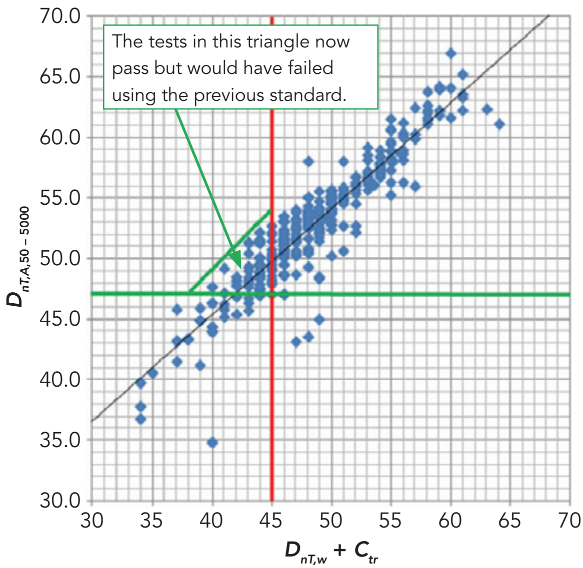

Figure 4.7. The effect of selecting the lowest value in the translation range.

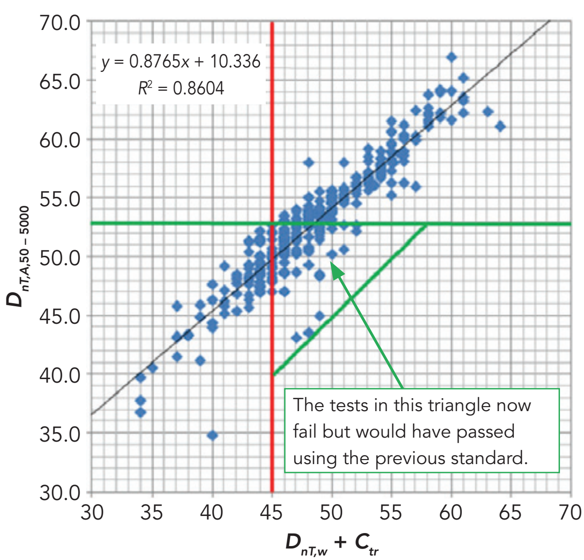

Figure 4.8. The effect of selecting the highest value in the translation range.

In other words, is this statistical translation the same for lightweight structure and heavy constructions?

The sixty three test results shown in Figure 4.6 were organized into heavy and lightweight structures. Only seven of the available tests were for lightweight constructions and consequently no conclusions can be drawn from such a limited amount of data. If predominantly lightweight constructions are used in a particular country, then the statistical approach will need to focus on that type of construction.

4.3.2. Other descriptors

The other reverberation time referenced descriptor in use is $D_{nT,w}$. In Scotland, the building regulations limit for airborne sound insulation is a minimum of 56 dB ($D_{nT,w}$). The available data set had 205 examples of tests that produced exactly 56 dB ($D_{nT,w}$) as shown in Figure 4.9.

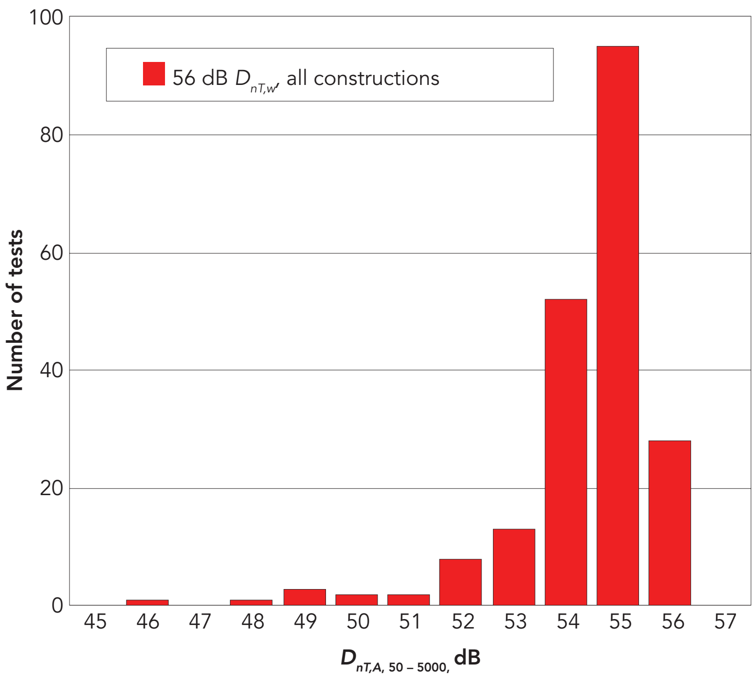

Figure 4.9. *Statistical distribution of all tests that exactly measured 56 dB ($D_{nT,w}$).*

At first glance this seems to be quite a wide spread of values that do not appear to be distributed in a Gaussian curve. However the data set included nineteen samples of lightweight construction and when these were removed the distribution as in Figure 4.10a resulted.

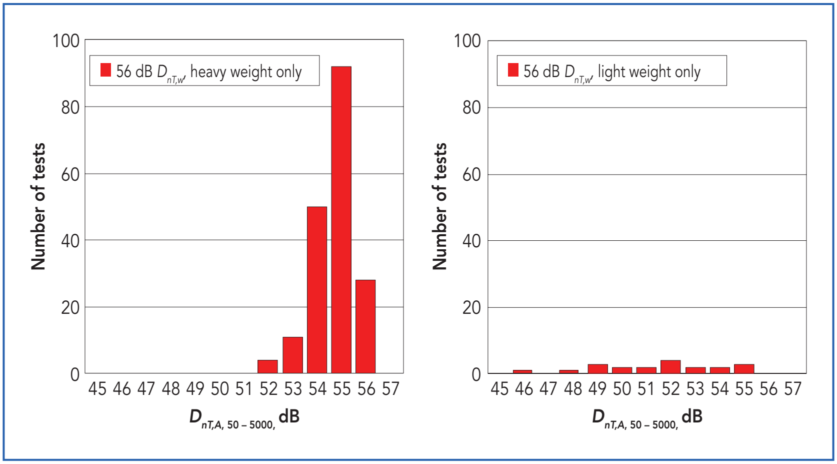

Figure 4.10. *Statistical distribution of tests on (a) only heavyweight constructions* and (b) *only light weight constructions, both exactly measured 56 dB* ($D_{nT,w}$).

It could be argued that the distribution is $D_{nT,A,50\text{-}5000}$ = 55 dB +/- 1dB. The theoretical translation in this case results in 54,4 dB, again quite a good agreement. In Scotland, building regulations only have one criterion for all constructions rather than separate criteria for heavyweight and lightweight constructions. The logical consequence of this is that if the translation of the descriptor is based on just the heavy constructions it would penalise lightweight constructions which, as Figure 4.10b shows, would mostly fail to achieve the same values of $D_{nT,A,50\text{-}5000}$.

However, in order to make an informed decision about the setting of an equivalent limit using the new descriptors, much more data would be required. It is clear that each countries acousticians will need to guide the respective government agency responsible for building regulations on how to use a statistical approach to establishing new limit values.

4.4. Conclusion

The statistical approach to the translation between the current and the new descriptors confirms, for the situation considered, the theoretical/

empirical translation on average, but also clearly indicates the spread around this average and the effect of building system. Such spreads need to be considered to see the practical consequences of a change. This statistical approach to the translation of a limit from one descriptor to the new descriptor would need to be undertaken in each country, at least with a variety in typical constructions, dimensions and currently used quantities.

Over half of the countries involved in COST TU0901 would also need to convert from an '*R*' based value to a 'D' based value so, for those countries, the translation is more involved. It is clear that the acousticians in each country will need to advise their respective governments on how to translate their existing limits.

4.5. References

[1] EN 12354-3, *Building Acoustics- Estimation of acoustic performance of buildings from the performance of elements, part 3: airborne sound insulation against outdoor sound*, CEN, 2000.

[2] Drasko Masovic, Kestutis Miskinis, Mete Oguc, Fabio Scamoni and Chiara Scrosati, *Analysis of Façade Sound Insulation Field Measurements - Influence of Acoustic And Non-Acoustic Parameters*, Internoise 2013, Innsbruck, Austria, 2013.

[3] Scholl, Lang & Wittstock. *Rating of sound insulation at present and in the future. The revision of ISO 717*, Acta Acustica **97**(2011), 686-698.

[4] Gerretsen, E., *A new system for rating impact sound insulation*, Applied Acoustics **9** (1976), 247-263.

[5] C. Rodrigues, A. Monteiro, C. Mondaca Marino, M. Machimbarrena, F. Torchia, E. Nannipieri, N. Robertson, R.S. Smith, *Comparative analyses of airborne sound insulation field measurements using different ISO 717-1 performance descriptors – Lightweight separating walls and floors & Heavyweight separating walls and floors*, Euronoise 2012, Prague, Czech Republic, 2012.

[6] www.costtu0901.eu

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5

Proposal for an Acoustic Classification Scheme for Housing

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CHAPTER 5 Proposal for an Acoustic Classification Scheme for Housing

5.1. Introduction

Classification schemes specify different quality levels of the acoustic performance for airborne and impact sound insulation, protection against outdoor sound and sound due to service equipment. Based on the lessons learned from existing classification schemes and from regulatory requirements in Europe, a balanced European scheme has been proposed, using the acoustic descriptors recommended by TU0901 (see Chapter 3 about descriptors). A review of existing classification schemes is shown in Chapter 2, and summary information is presented in 5.2 as a background for the considerations in 5.3 about development of the TU0901 proposal. The complete TU0901 proposal is presented in 5.4.

5.2. Existing acoustic classification schemes for housing

Table 2.8, gives an overview of the existing classification schemes in Europe. Only schemes with a minimum of three levels are included, thus excluding regulatory documents indicating only a main level and an enhanced level. Details on descriptors used in existing schemes can be found in references in Chapters 2 and 5.4.11, and some indications are found in Chapter 2, mainly in Figures 2.7 and 2.8.

For decisions on future class criteria compared to existing schemes, a comparison between the schemes must be based on translation of the applied descriptors into common, proposed descriptors. For regulatory requirements, this is already partly done in Figures 2.2 and 2.3 with limit values converted to common descriptors for comparability - down to 100 Hz only as currently applied in most countries. The issue is further elaborated in [9] using the descriptors proposed in Chapter 3. The results are used to get an indication of the steps between classes and the total range of existing class criteria. An illustration of this is given in Figure 5.1 for airborne and impact sound.

The results in Figure 5.1 can be compared with the Figures 2.7 and 2.8 in which the class criteria are shown without translation, thus illustrating the present chaotic situation. The figures also show that the regulatory

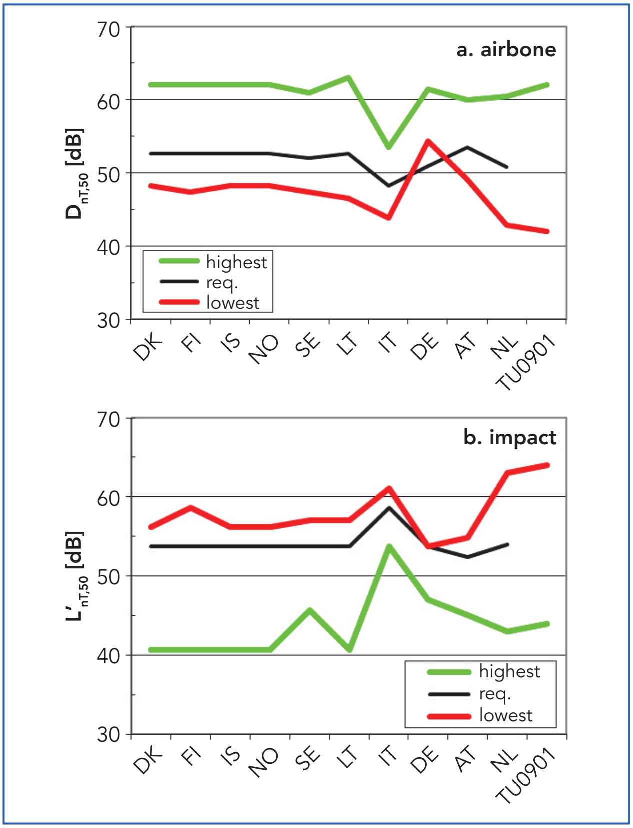

Figure 5.1. *Airborne (a) and impact (b) sound insulation limits for highest and lowest classes in 10 classification schemes in Europe and regulatory requirements for the same countries, all after translation to proposed descriptors (cf. Figures 2.7 and 2.8).*

requirements in countries with existing classification schemes are much closer to the lowest class than the highest class in most cases, thus tending not to consider classification of older, lower performing housing in which the sound insulation is well below the regulatory limit.

5.3. Considerations and decisions during development of proposal

The starting point for the definition of the quality levels is the summary of descriptors presented in Chapter 3. The descriptors cover the frequency range from 50 Hz to 3150/2500 Hz, but starting at 100 Hz is also considered by using a slightly adjusted class denotation, e.g. X_{100} instead of just X, see 5.4.

Class criteria are included for airborne and impact sound insulation between dwellings, for indoor levels due to outdoor sound or facade sound insulation and for sound levels due to service equipment. Criteria are also recommended for reverberation time in stairwells and common access areas, but only for optional use and not as an element in the classification of a dwelling.

For the steps between classes 4 dB is chosen for all aspects. This is close to the average for the existing schemes for airborne and impact sound insulation, see Chapter 2, corresponds to a substantial step in subjective assessment and also allows easy subdivision for special cases. To cover approximately the whole range of existing classes and most requirements, the proposed classification scheme specifies six classes A-F, thus covering a range of 20 dB, and in addition the denotation npd (no performance determined).

It is felt important to express the meaning of a class in neutral wording as far as possible. The classes for the different aspects are grouped in such a way that globally all aspects (sound insulation and equipment sound) within a specific class are assessed as equally annoying or (dis)satisfying. For such considerations, indications in various classification documents were used, the percentages coming mainly from the present Danish and Dutch classification schemes.

A dwelling can be classified in a specific environment by specifying a limit for the indoor sound levels or for the required facade sound insulation by taking into account the noise exposure L_{den} for that environment. If the environment is not known, the dwelling can be classified in a general suburban environment characterised by an outdoor noise exposure of L_{den} = 55 dB. For balanced comfort, the requirements for a facade should not be too high to allow some acoustical contact with outdoors and to avoid more disturbance by neighbour sounds due to less masking by traffic noise. This means that increasing the sound insulation above a certain value does not result in a higher quality class.

Dwellings can be classified individually or as a whole residential building, if all dwellings fulfil criteria – or even for an individual room. Compliance criteria for class designation are described in 5.4.8. However, further discussions and specifications are needed, for instance on how to integrate calculations at the design stage according to EN 12354 in the assessment procedure.

For traditional heavy buildings the airborne and impact sound insulation with and without the low frequencies down to 50 Hz differ only marginally. It is thus decided to maintain the same limits for class X and class X_{100} with the clear warning that X_{100} fails to deal adequately with some lightweight and other double constructions.

Based on these considerations – and after having discussed different acoustic characteristics separately - a first complete draft was sent to TU0901 members for comment. Comments were received from 14 countries, often in much detail (28 pages in total). Many of these comments were taken into account for a revised draft presented at the next TU0901 meeting, and further adjustments were made before finalizing the current proposal found in 5.4. Nevertheless, various details need further discussion before a practical working system is reached, and other issues like sound insulation internally in dwellings and classification of environment could be considered as optional or mandatory parts of a classification.

The whole process involved several TU0901 member countries which had no existing classification scheme, and thus an adaptation to the whole idea of a classification has started.

The TU0901 proposal for a classification scheme will be presented to standardization groups in ISO and CEN aiming at further development of the proposal to become a European or even world-wide scheme, thus also reminding people and the building industry about the possibility of integrating the specification of acoustic conditions on equal terms with other qualities for new and renovated housing.

5.3.1. Comparison of proposed classification scheme with current national requirements

It is intended that each country could choose a class as the national regulatory limit. Countries having stricter requirements or class criteria for row housing could then choose one class higher for such housing.

To illustrate the consequences of the proposed system in relation to the current requirements in different countries, a comparison is made for multi-storey housing in Figure 5.2 based on the overview of the current national requirements as collected during this action, translated into the proposed

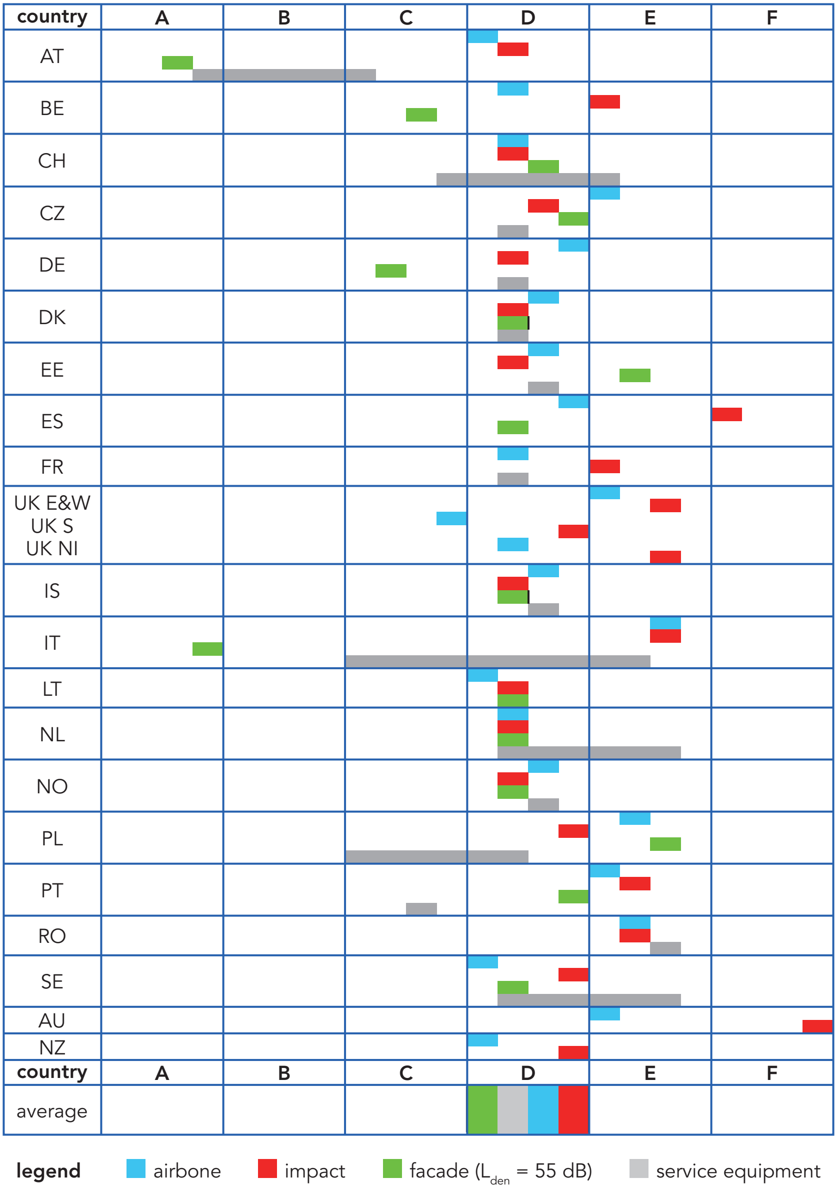

Figure 5.2. Overview of the classes corresponding to the translated current requirements in the indicated countries. Based on requirements reported from TU0901 members in 19 Countries (UK considered one country), ref. [9].

descriptors and then compared with the proposed classification system. For facades, the different requirements are transferred into the required facade insulation for an outdoor noise exposure of L_{den} = 55 dB. For sound due to service equipment often a range is indicated, if requirements differentiate between quantities (L_{eq} and L_{max}) or type of equipment.

The countries and numbers considered here in this Chapter 5 do not correspond exactly with what is presented in Chapter 2 with independent studies started several years before TU0901 and later updated and extended to as many countries as possible. Chapter 5 is based on data reporting from TU0901 members, and not all countries responded. However, these differences do not influence the general trends in the data presented here.

It is clear from Figure 5.2 that the current situation for the requirements on average is characterised as class D albeit with large deviations for service equipment and facades. Several countries might expect a higher class in a new scheme, cf. Table 2.8, and thus a discussion on shift of criteria to one class higher might be foreseen.

5.4. TU0901 Proposal: Acoustic classification scheme for dwellings

5.4.1. Introduction - scope

The TU0901 acoustic classification scheme for dwellings has been developed by COST Action TU0901 "Integrating and Harmonizing Sound Insulation Aspects in Sustainable Urban Housing Constructions". The purpose of the classification scheme is to make it easier for developers to specify and for users to require or be informed about a standardized acoustic quality other than the quality defined by regulations. The classification scheme can also be applied as a general tool to characterise the quality of the existing housing stock and includes provisions for classifying the acoustic quality after renovations have taken place. An additional purpose of the classification scheme is that national authorities can define a specific class in building regulations as the minimum requirement for acoustic conditions in dwellings.

In most countries in Europe, building regulations specify minimum requirements about acoustical conditions for new dwellings. However, complying with regulatory requirements does not guarantee satisfactory conditions for the occupants, and thus there is a need for a classification scheme with classes reflecting different levels of acoustical comfort.

The classification scheme specifies criteria for six classes A, B, C, D, E and F for dwellings, class A being the highest class and F the lowest class. If no acoustic performance is required or the performance is outside the indicated classes or not determined, it can be classified as npd (no performance determined).

The classification includes as class criteria for the above classes minimum values for airborne sound insulation, maximum values for impact sound pressure level and sound pressure levels in the dwellings from service equipment and maximum indoor sound levels or minimum values for insulation from outdoor noise from traffic, industry or other sources in order to assure maximum indoor levels of such sources. Furthermore, maximum values for reverberation time classes for stairwells and common access areas are included as an option for classification, but not a mandatory part of classification of dwellings or buildings.

A classification can be made for a dwelling or for a residential building, if all dwellings in the building fulfil class criteria or even for an individual room. All the requirements given for a class for each acoustic characteristic (sound insulation etc.) shall be fulfilled in order to obtain a classification with a certain class designation. The classification applies as long as there are no adverse changes in building constructions or environment. If such changes occur, the classification shall be reconsidered. Dwellings in building can also be assigned different classes.

The classification of a dwelling or a residential building is based in principle on measurements in accordance with the compliance procedure defined in the scheme. In the design stage an estimate can be made only on the basis of prediction, and predicted performance values could be included in the evaluation in a safe way to enhance the basis for classification.

5.4.2. Normative references

EN ISO 717-1:2013 Acoustics — Rating of sound insulation in buildings and of building elements — Part 1: Airborne sound insulation

EN ISO 717-2:2013 Acoustics - Rating of sound insulation in buildings and of building elements — Part 2: Impact sound insulation

EN ISO 140-4:1998 Acoustics — Measurement of sound insulation in buildings and of building elements — Part 4: Field measurements of airborne sound insulation between rooms. *Note:* To be replaced by ISO/FDIS 16283-1, Acoustics — Field measurement of sound insulation in buildings and of building elements — Part 1: Airborne sound insulation

EN ISO 140-5:1998 Acoustics — Measurement of sound insulation in buildings and of building elements — Part 5: Field measurements of airborne sound insulation of facade elements and facades. *Note:* To be replaced by ISO/NP 16283-3, Acoustics — Field measurement of sound insulation in buildings and of building elements — Part 3: Facade sound insulation

EN ISO 140-7:1998 Acoustics - Measurement of sound insulation in buildings and of building elements — Part 7: Field measurements of impact sound insulation of floors *Note:* To be replaced by ISO/CD 16283-2, Acoustics — Field measurement of sound insulation in buildings and of building elements — Part 2: Impact sound insulation

EN ISO 3382-2:2008 + Cor 1:2009 Acoustics — Measurement of room acoustic parameters — Part 2: Reverberation time in ordinary rooms

EN 12354-1:2000 (ISO 15712-1:2005) Building acoustics — Estimation of acoustic performance of buildings from the performance of elements — Part 1: Airborne sound insulation between rooms

EN 12354-2:2000 (ISO 15712-2:2005) Building acoustics — Estimation of acoustic performance of buildings from the performance of elements — Part 2: Impact sound insulation between rooms

EN 12354-3:2000 (ISO 15712-2:2005) Building acoustics — Estimation of acoustic performance of buildings from the performance of elements — Part 3: Airborne sound insulation against outdoor sound

EN ISO 10052:2004 Acoustics — Field measurements of airborne and impact sound insulation and of equipment noise — Survey methods. + Amd 1:2010

EN ISO 16032:2004 Acoustics — Measurement of noise from service equipment in buildings — Engineering method

5.4.3. Definitions

For the purpose of this TU0901 proposal for a classification scheme the following definitions apply:

Classes A, B, C, D, E, F and npd

Six classes A-F specifying different levels of acoustic conditions in dwellings. Class A is the highest class, class F the lowest class. The meaning of classes is explained in 5.4.10. The indication npd can be used for dwellings were no acoustic performance is required or determined or if the performance does not even comply with class F. For sound insulation (airborne and impact), the default frequency range is 50 Hz to 3150 Hz. However, an alternative frequency range 100-3150 Hz is possible resulting in a class denotation X_{100}, e.g. B_{100}.

Airborne sound insulation between rooms

This is the characteristic of a building construction to insulate against airborne sound transmission in a building. The measurement result is given as a single-number quantity expressed in decibels (dB).

The specified class limits are related to measurements in situ in frequency bands according to EN ISO 140-4, and evaluation according to EN ISO 717-1 and expressed in the descriptor: $D_{nT,50} = D_{nT,w} + C_{50\text{-}3150}$ as defined in EN ISO 717-1.

As an alternative to $D_{nT,50}$, the performance can be estimated for all types of construction by the currently more common descriptor $D_{nT,100} = D_{nT,w} + C$ as also determined according to EN ISO 717-1. However, in case of light-weight building constructions and composed elements with low frequency resonances, the evaluation will most likely not be safe. If $D_{nT,100}$ is applied, the class denotation is X_{100}, e.g. B_{100}.

Impact sound pressure level

This characterises the extent to which a building construction transfers impact sound within the building. The measurement result is given as a single-number quantity s expressed in decibels (dB).

The specified class limits are related to measurements in situ in frequency bands according to EN ISO 140-7, and evaluation according to EN ISO 717-2 and expressed in the descriptor: $L'_{nT,50} = L'_{nT,w} + C_{I,50\text{-}2500}$ as defined in EN ISO 717-2.

Experience has shown that when applying this low-frequency rating, potentially disturbing high frequency sounds are not rated appropriately. For this reason, an additional criterion for $L'_{nT,w}$ is applied with the same limit value, while awaiting a future improved weighting procedure that solves this problem adequately.

As an alternative to $L'_{nT,50}$, the performance can be estimated for all types of constructions by the currently more common descriptor $L'_{nT,100} = L'_{nT,w} + C_I$ as also determined according to EN ISO 717-1. However, in case of light-weight building constructions and composed elements with low frequency resonances the evaluation will most likely not be safe. If $L'_{nT,100}$ is applied, the class denotation is X_{100} , eg. B_{100}.

Airborne sound insulation of facades

This characterises the facade's ability to insulate against airborne sound transmission into a building. The measurement result is given as a single-number quantity expressed in decibels (dB).

The specified limits are related to measurements in situ in frequency bands according to EN ISO 140-5, and evaluation according to EN ISO 717-1, and expressed in the descriptor: $D_{2m,nT,50} = D_{2m,nT} + C_{tr,50\text{-}3150}$ or $+ C_{50\text{-}3150}$, depending on type of outdoor noise and as defined in EN ISO 717-1

As an alternative to $D_{2m,nT,50}$, the performance can be estimated for all types of construction by the currently more common descriptor $D_{2m,T,100} = D_{2m,nT,w} + C_{tr}$ or C as also determined according to EN ISO 717-1. However, in case of light-weight building constructions and composed elements with low frequency resonances, the evaluation will most likely not be safe. If $D_{2m,nT,100}$ is applied, the class denotation is X_{100}, eg. B_{100}.

Service equipment sound pressure level

This characterises the received sound pressure level in rooms due to the operation of a specific piece of service equipment or plant in a building. The measurement result is given as a single-number quantity expressed in decibels (dB). The specified limits are related to measurements in situ, either in frequency bands in accordance with EN ISO 16032 or directly in A-weighted levels in accordance with EN ISO 10052. The measurements concern either the A-weighted equivalent sound level or the A-weighted maximum F sound level during a specified working cycle of considered equipment. These working conditions are specified for various types of equipment in the mentioned standards. The descriptors are L_{eq} and L_{maxF} , resp. $L_{eq,nT,A}$ and $L_{maxF,nT,A}$ as defined in EN ISO 16032 and EN ISO 10052.

Reverberation time

The time that would be required for the sound pressure level to decrease by 60 dB after the sound source has stopped. The quantity is denoted by T, and is expressed in seconds (s).

The specified limits are related to space averaged reverberation times in each of the octave bands 250, 500 1000 and 2000 Hz.

Measurements are carried out according to EN ISO 3382-2.

5.4.4. Airborne & Impact sound insulation

The minimum values of the classes for airborne sound insulation are shown in Table 5.1.

Table 5.1. *Airborne sound insulation between dwellings and other rooms. Class limits.*[(1),(2)]

Type of space	Class A $D_{nT,50}$ (dB)	Class B $D_{nT,50}$ (dB)	Class C $D_{nT,50}$ (dB)	Class D $D_{nT,50}$ (dB)	Class E $D_{nT,50}$ (dB)	Class F $D_{nT,50}$ (dB)
Between a dwelling and premises with noisy activities [(3)]	≥ 68	≥ 64	≥ 60	≥ 56	≥ 52	≥ 48
Between a dwelling and other dwellings and rooms outside the dwelling	≥ 62	≥ 58	≥ 54	≥ 50	≥ 46	≥ 42

NOTES

(1) $D_{nT,50} = D_{nT,w} + C_{50\text{-}3150}$;

(2) As an alternative to $D_{nT,50}$, the performance can be estimated for all types of construction by the currently more common descriptor $D_{nT,100} = D_{nT,w} + C$, see clause 3. If $D_{nT,100}$ is applied, the class denotation is X_{100}, eg. B_{100}.

(3) Premises with noisy activities are rooms for shared services like laundries, central boiler house, joint/commercial kitchens or commercial premises like shops, workshops or cafés. However, in each case, noise levels must be estimated and the sound insulation designed accordingly, e.g. for party rooms, discotheques etc. Offices are normally not considered as noisy premises, and the same criteria as for dwellings apply.

The maximum values of the classes for impact sound pressure level are shown in Table 5.2.

5.4.5. Facade sound insulation

The facade sound insulation shall assure an indoor sound level for which the maximum class limits are shown in Table 5.3a. This can be achieved in two ways: by specifying these maximum indoor levels or by specifying a minimum facade sound insulation on the bases of the outdoor sound impact ($D_{2m,nT,50} = L_{den} + 3 - L_{den,indoor}$). In the latter case the minimum values for the classes of the facade sound insulation are shown in Table 3b, either for a general suburban environment or for a specific environment as characterised by L_{den} for the relevant outdoor sound sources.

Table 5.2. *Impact sound pressure level in dwellings. Class limits.*(1),(2),(3)

Type of space	Class A $L'_{nT,50}$ (dB)	Class B $L'_{nT,50}$ (dB)	Class C $L'_{nT,50}$ (dB)	Class D $L'_{nT,50}$ (dB)	Class E $L'_{nT,50}$ (dB)	Class F $L'_{nT,50}$ (dB)
In dwellings from premises with noisy activities(4)	≤ 38	≤ 42	≤ 46	≤ 50	≤ 54	≤ 58
In dwellings from other dwellings	≤ 44	≤ 48	≤ 52	≤ 56	≤ 60	≤ 64
In dwellings: – from common stairwells and access areas – balconies, terraces, bath, toilet not belonging to own dwelling	≤ 48	≤ 52	≤ 56	≤ 60	≤ 64	≤ 70

NOTES

(1) $L'_{nT,50} = L'_{nT,w} + C_{I,50\text{-}2500}$

(2) The same limit values are to be fulfilled by $L'_{nT,w}$.

(3) As an alternative to $L'_{nT,50}$, the performance can be estimated for all types of constructions by the currently more common descriptor $L'_{nT,100} = L'_{nT,w} + C_I$, see Clause 3. If $L'_{nT,100}$ is applied, the class denotation is X_{100}, eg. B_{100}.

(4) Premises with noisy activities are rooms for shared services like laundries, central boiler house, joint/commercial kitchens or commercial premises like shops, workshops or cafés. However, in each case, noise levels must be estimated and the sound insulation designed accordingly, e.g. for party rooms, discotheques etc. Offices are normally not considered as noisy premises, and the same criteria as for dwellings apply.

If fulfilling these limits requires a very high facade sound insulation, say more than $D_{2m,nT,50} \geq 35$ dB, it is questionable whether the overall quality is really increased (less contact with living environment, sounds from the neighbour more audible) and therefore assigning a high class could be restricted.

Table 5.3a. *Sound levels in dwellings due to outdoor sounds. Class limits.*(1)

Type of space	Class A $L_{den,indoor}$ (dB)	Class B $L_{den,indoor}$ (dB)	Class C $L_{den,indoor}$ (dB)	Class D $L_{den,indoor}$ (dB)	Class E $L_{den,indoor}$ (dB)	Class F $L_{den,indoor}$ (dB)
In dwellings from outdoor sound sources; for each type of source	≤ **23**	≤ **27**	≤ **31**	≤ **35**	≤ **39**	≤ **43**

NOTES

(1) $L_{den,indoor}$ is the normalized A-weighted indoor sound level with weighting of the day, evening, night period over the frequency range from 50 Hz to 5000 Hz as defined in the END for outdoor sound.

Table 5.3b. *Facade sound insulation in dwellings. Class limits.*[(1), (2)]

Type of space	Class A $D_{2m,nT,50}$ (dB)	Class B $D_{2m,nT,50}$ (dB)	Class C $D_{2m,nT,50}$ (dB)	Class D $D_{2m,nT,50}$ (dB)	Class E $D_{2m,nT,50}$ (dB)	Class F $D_{2m,nT,50}$ (dB)
In dwellings from outdoors; general suburban environment L_{den} = 55 dB.[(3)]	≥ 35	≥ 31	≥ 27	≥ 23	≥ 19	≥ 15
In dwellings from outdoors; specific environment with sound sources characterised by L_{den}.[(4),(5)]	≥ L_{den}-20	≥ L_{den}-24	≥ L_{den}-28	≥ L_{den}-32	≥ L_{den}-36	≥ L_{den}-40

NOTES

(1) $D_{2m,nT,50} = D_{2m,nT,w} + C_{tr,50\text{-}3150}$ in general. However, if the type of outdoor source is better characterised by the C spectrum, for instance for some types of railway traffic, $D_{2m,nT,50} = D_{2m,nT,w} + C_{50\text{-}3150}$ can be used. In some countries this performance applies to a ventilated facade according to ventilation requirements

(2) As an alternative to $D_{2m,nT,50}$ the performance can be estimated for all types of constructions by the currently more common descriptor $D_{2m,nT,100} = D_{2m,nT,w} + C_{tr}$ (or $=D_{2m,nT,w} + C$), see Clause 3. If $D_{2m,nT,100}$ is applied, the class denotation is X_{100}, e.g. B_{100}.

(3) L_{den} is the free field level for the general outdoor traffic sound as defined for the END; the typical background sound levels in this environment will be 45-50 dB in daytime.

(4) L_{den} is the free field level for the relevant outdoor sound sources as defined for the END.

(5) For a classification including the environment the requirement must be increased in the same amount as the noise impact is higher than L_{den} = 55 dB as is indicated in the third row.

5.4.6. Noise from building service equipment

The maximum values of the classes for sound levels due to service equipment are shown in Table 5.4.

5.4.7. Reverberation time in stairwells and joint access areas

Classification of reverberation time is an option, but not a mandatory part of classification of dwellings or buildings. The results can be given as additional information or omitted (in which case npd is indicated).

The maximum values of the classes for reverberation time are shown in Table 5.5.

Table 5.4. *Sound levels in dwellings due to building service equipment. Class limits.*[(1)]

Type of space and sources [(2)]	Class A L_{eq} or L_{maxF} (dB)	Class B L_{eq} or L_{maxF} (dB)	Class C L_{eq} or L_{maxF} (dB)	Class D L_{eq} or L_{maxF} (dB)	Class E L_{eq} or L_{maxF} (dB)	Class F L_{eq} or L_{maxF} (dB)
In dwellings due to ventilation / heating / cooling installation L_{eq}.	≤ 20	≤ 24	≤ 28	≤ 32	≤ 36	≤ 40
In dwellings due to use of toilet, bath, shower in neighbour dwellings L_{maxF}.	≤ 20	≤ 24	≤ 28	≤ 32	≤ 36	≤ 40
In dwellings due to other sources (lift, water supply, pumps, garage doors, etc.) L_{maxF}.	≤ 25	≤ 29	≤ 33	≤ 37	≤ 41	≤ 45

NOTES

(1) L_{eq} and L_{maxF} are resp. $L_{A,eq,nT}$ and $L_{AF,max,nT}$ as defined in ISO 16032 and ISO 10052

(2) Requirements relate to sounds that occur more than occasionally due to service equipment in neighbouring dwellings, general equipment serving the whole building and service equipment in the own dwelling for ventilation / heating / cooling.

Table 5.5. *Reverberation time, maximum values for T. Class limits.*

Type of space	Class A T (s)	Class B T (s)	Class C T (s)	Class D T (s)	Class E T (s)	Class F T (s)
Common stairwells and joint access areas	≤ 0,8	≤ 1,0	≤ 1,3	≤ 1,6	≤ 2,0	≤ 2,5

NOTES

(1) The limits are averaged reverberation times and apply in each of the octave bands 250, 500, 1000 and 2000 Hz, see Clause 3.

(2) Since often measuring and predicting the reverberation time is rather difficult and inaccurate in such enclosed areas, the requirement on the reverberation time could be replaced by one on the calculated amount of applied equivalent absorption area $A \geq 0{,}16\ V / T_{limit}$.

5.4.8. Guidelines for verification of compliance with an acoustic class

5.4.8.1. General

The aim of this guideline is to facilitate national implementation of this classification scheme and practical application of the acoustic classification of a residential building, individual dwellings or even a room or a specific acoustic characteristic for a room, in the following denoted a unit.

The following conditions should be considered when a unit is subject to an evaluation of compliance with the criteria of a specific acoustic class.

The classification of a unit applies from a certain date. The classification is valid as long as the building constructions remain unaltered. If changes occur, the classification has to be reconsidered. This may for instance be relevant in case of changes in constructions or in outdoor noise conditions. In the design stage of a building or in case of changes in a building, an estimation of the class can only be determined by calculations; it is advisable to keep then a safety margin of at least half a class (2 dB).

5.4.8.2. Verification of compliance with criteria for an acoustic class

The compliance of a unit with a class is documented by measurements in the completed unit. Acoustic measurements are performed according to the relevant standards specified in the main body of this classification scheme in order to verify the compliance with the class criteria. The persons or organizations that are appointed to make the relevant measurements shall be qualified for the task. The contents of a report of acoustic classification are given in Clause 5.4.8.3.

General principles

When verifying the acoustic class of a unit, the general principle is that a sufficient number of measurements of each relevant acoustic characteristic must be performed in order for the result to represent the unit. Care should be taken to include the critical sites/rooms, e.g. partitions with critical flanking constructions. To enhance the basis for classification, performance predictions by calculation may be a supplement to the measurements, applying a sufficient safety margin. An expert in acoustics selects the structures and spaces to be measured in such a way that they are sufficiently representative of the unit. It must be noted that in order to achieve the class set as a goal, all measurement results must in principle meet the criteria of the class in question. However, compliance is granted, if the average results comply with class limits, and no individual result deviates adversely by more than 2 dB.

If classification for different dwellings, rooms or acoustic characteristics varies, the classification assigned is the minimum class obtained, when considering all relevant acoustic characteristics. However, additional assignments of higher classes for individual dwellings, rooms or acoustic characteristics can be made according to the rules for such units, see below.

If for sound insulation, the alternative frequency range down to 100 Hz is applied, the class denotation is X_{100} , eg. B_{100}, and the same rules for assigning a class are applied. One then must realize X_{100} fails to deal adequately with some lightweight and other double constructions.

If no acoustic performance is required or the performance is outside the indicated classes or not determined, it can be declared as npd (no performance determined).

Verification of an entire building

When an entire building is to be tested, the number of samples for measurement of airborne and impact-sound insulation and noise levels is 5% of the spaces or structures. However, the minimum number of measurements for each structure type and acoustic characteristic is always 3.

Verification of individual dwellings, rooms or acoustic characteristic

Individual dwellings, rooms or acoustic characteristic in a building may be classified, if each of them complies with the relevant class limits. The above-mentioned general principles apply.

Minimum number of measurements for each type of structure, room or acoustic characteristic is normally two.

5.4.8.3. Contents of verification report for classification of a dwelling or building

Reports, in which the acoustic classification of a dwelling or a building is presented according to this classification scheme, must be uniform and concise. The first page of the report should contain only the most essential information, such as the objective of the measurements, the client, name of the person(s) or organization responsible for the verification, the number of dwellings verified, the measurements dates, the main results, the class obtained, other relevant information, a reference to this classification scheme and signatures.

Detailed information about measurement methods, the dwelling(s) or building and the measurement results should be presented in appendices of the classification report. Reference should be made to the specific test reports (with frequency dependent results) being the basis of the class assignment.

In case of different classes for different dwellings, rooms or acoustic characteristics, the report could include overview tables with classes obtained for the different acoustic characteristics and/or for different dwellings or rooms.

5.4.9. Classification examples

Four examples are shown below for the presentation of classification results determined according to the procedure in 8.2. In all cases the verification report must include information as described in 8.3. The four examples are:

1. Classification of a residential building with one class for the entire building.
2. Classification of a dwelling with one class for the entire dwelling.
3. Classification of a residential building with individual class indication for each acoustic characteristic.
4. Classification of a dwelling with individual class indication for each acoustic characteristic.

Example 1: A residential building has obtained Class D, as a minimum this class has been fulfilled for all individual acoustic characteristics.

Example 2: A dwelling No. NNN has obtained Class C, as a minimum this class has been fulfilled for all individual acoustic characteristics for the dwelling.

Example 3: Classification of a residential building with individual class indication for each acoustic characteristic.

Acoustic classification of residential building with several dwellings and no noisy premises							
Acoustic characteristic	Class						
	A	B	C	D	E	F	npd
Airborne sound insulation				X			
Impact sound pressure level				X			
Facade sound insulation			X				
Noise from building service equipment			X				
Rev.time in stairwells etc. (optional)							X

The classification result for the entire building is Class D, which is the lowest class for individual acoustic characteristics.

Example 4: Classification of a dwelling with individual class indication for each acoustic characteristic.

Acoustic classification of dwelling No. NNN in residential building with no noisy premises							
Acoustic characteristic	Class						
	A	B	C	D	E	F	npd
Airborne sound insulation			X				
Impact sound pressure level			X				
Facade sound insulation		X					
Noise from building service equipment			X				
Rev.time in stairwells etc. (optional)							X

The classification result for the entire dwelling is Class C, which is the lowest class for individual acoustic characteristics.

5.4.10. Explanation of meaning of classes

Table 5.6. *Description in general terms of the quality of the different classes*

Class	General	Sound insulation judged poor
A	A quiet atmosphere with a high level of protection against sound	less than 5%
B	Under normal circumstances a good protection without too much restriction to the behaviour of the occupants	around 5%
C	Protection against unbearable disturbance under normal behaviour of the occupants, bearing in mind their neighbours	around 10%
D	Regularly disturbance by noise, even in case of comparable behaviour of occupants, adjusted to neighbours	around 20%
E	Hardly any protection is offered against intruding sounds	around 35%
F	No protection is offered against intruding sounds	50% or more

NOTE: the indicated percentages are just a global indication; the trend is rather well based in literature, but the absolute numbers depend very much on the setting and wording of questionnaires used.

Table 5.7. *Global indication of what can be expected for some airborne and impact sound sources.*

Sources:	A	B	C	D	E	F
very loud speech	just audible, but not intelligible	audible, but hardly intelligible	just intelligible	intelligible	clearly intelligible	
loud speech	hardly audible	just audible, but not intelligible	audible, but hardly intelligible	just intelligible	intelligible	clearly intelligible
normal speech	not audible	hardly audible	just audible but not intelligible	hardly intelligible	just intelligible	intelligible
very loud music, party	just audible	audible	clearly audible	very clearly audible		
loud music	not audible	just audible	audible	clearly audible	very clearly audible	
normal music	not audible		just audible	audible	clearly audible	very clearly audible
walking	not audible	hardly audible	just audible	audible	clearly audible	very clearly audible
kids playing	hardly audible	Just audible	audible	clearly audible	very clearly audible	
dropping & moving objects	not audible	hardly audible	just audible	audible	clearly audible	very clearly audible

NOTE: if sounds are audible depends not only on the building construction but also on the background noise of the environment. These descriptions reflect the average situation in a reasonably quiet suburban environment, as is the basis for the general classification of the facade sound insulation. In a quieter environment the description will shift to the left, while in a noisier environment the description will shift to the right.

5.4.11. References

The below references are related to publications with overview descriptors, regulations and classification schemes in Europe or to principles of classification schemes. Exact references for national classification schemes are found in the below overview publications.

[1] *"Acoustic quality and sound insulation between dwellings"* by J.H. Rindel, Journal of Building Acoustics, 1999, Vol. 5, pp. 291-301.

[2] *"Sound Classification of Dwellings – Quality Class Ranges and Class Intervals in National Schemes in Europe"* by B. Rasmussen. EuroNoise 2012, Prague, Czech Republic, 2012. http://vbn.aau.dk/en/persons/birgit-rasmussen(c0e774a9-8cdf-410f-8727-6a2cc11a4f14)/publications.html

[3] *"Sound insulation between dwellings – Overview of the variety of descriptors and requirements in Europe"*, by B. Rasmussen, Forum Acusticum 2011, Aalborg, Denmark, Paper ID 573.Acustica United with Acta Acustica, 2011, Vol. 97 Supplement 1. http://vbn.aau.dk/en/persons/birgit-rasmussen(c0e774a9-8cdf-410f-8727-6a2cc11a4f14)/publications.html

[4] *"Harmonization of sound insulation descriptors and classification schemes in Europe: COST Action TU0901"* by Birgit Rasmussen. EAA TC-RBA & COST TU0901 Symposium, December 2010, Florence, Italy. http://vbn.aau.dk/en/persons/birgit-rasmussen(c0e774a9-8cdf-410f-8727-6a2cc11a4f14)/publications.html

[5] *"Sound classification of dwellings in the Nordic countries – Differences and similarities between the five national schemes"* by B. Rasmussen. BNAM 2012, Odense, Denmark, June 2012. http://vbn.aau.dk/en/persons/birgit-rasmussen(c0e774a9-8cdf-410f-8727-6a2cc11a4f14)/publications.html

[6] *"Sound insulation between dwellings – Descriptors in building regulations in Europe"* by Birgit Rasmussen & Jens Holger Rindel. Applied Acoustics, 2010, 71(3), 171-180. http://dx.doi.org/10.1016/j.apacoust.2009.05.002;

[7] *"Sound insulation between dwellings – Requirements in building regulations in Europe"* by Birgit Rasmussen. Applied Acoustics, 2010, 71(4), 373-385. http://dx.doi.org/10.1016/j.apacoust.2009.08.011;

[8] "Model-based assessment scheme for acoustic quality in buildings", by Eddy Gerretsen. NAG-DAGA 2009, Rotterdam.

[9] "European variety of descriptors for building acoustic performance and translation into proposed harmonized descriptors" by Eddy Gerretsen. InterNoise2013, Sept. 2013, Innsbruck, Austria.

Notes:

A list of published national classification schemes updated to March 2012 is found in ref. [2]. References [2]-[7] are based on analysis of published regulations and classification schemes, and studies are made independently from TU0901. Information in [9] may differ from [2]-[7], especially about classification schemes, because [9] is based on a survey in 2010-2011 with self-reported data from TU0901 members and also includes drafts and does not include all published classification schemes.

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6

Developing a Uniform Questionnaire for Socio-Acoustic Surveys in Residential Buildings

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CHAPTER 6 Developing a Uniform Questionnaire for Socio-Acoustic Surveys in Residential Buildings

6.1. Introduction

The purpose of this chapter is to document the development of a uniform template for a socio-acoustic questionnaire and some supporting documents. This work has been made by the working group 2 (WG 2) under the COST action TU 0901, from 2010 to 2013.

Noise from sources of different kinds in multi-storey residential buildings is often problematic to their occupants. The noise may be caused by the neighbours (music, conversation, walking, jumping, running and even pet noise) as well as service equipment or environmental activities (traffic, industrial noise). The European Construction Product Regulation states in its 5th essential requirement that new and renovated dwellings shall provide sufficient protection against noise (i.e. sound insulation) to allow privacy and reasonable activities without disturbing neighbours. Indeed, exposure to noise can have negative effects on a person's ability to communicate, relax and sleep, and it can generate health troubles, psychological disorders as well as conflicts. It is not necessarily the noisy event itself that is most problematic for health but rather, the lack of silent periods needed to recover.

The results from the World Health Organization's WHO "Lares" Survey about European housing (Large Analysis and Review of Housing and Health) carried out in 2002-2003 show that neighbour noise is a health problem and the reduction of indoor noise exposure was included in the proposed objectives for a policy with the following recommendation:

> *"Little attention was paid to neighbour noise till now and therefore pathological effects are considerably under-estimated. The health effect of neighbour noise induced annoyance is approximately in the same range as the health effect of traffic noise induced annoyance. The results point out, that it is necessary to improve the sound insulation in residential buildings. The cardio-respiratory system also reacts to neighbour noise with increased relative risks."* (http://www.euro.who.int/en/health-topics/environment-and-health/Housing-and-health/

activities/the-large-analysis-and-review-of-european-housing-and-health-status-lares-project)

Therefore, there is a need to improve the awareness in the construction sector of the negative effects of insufficient sound insulation on dwelling occupants. Sustainable building and urban development as well as certification schemes should take into account the acoustic and sound insulation requirements.

The main task of the COST TU0901 Action was to propose harmonized criteria for sound insulation and a classification scheme for residential buildings in Europe. To choose suitable criteria, it was essential to establish statistical relationships between the average reaction of occupants of a building to noise and the physical single number quantities that can either be predicted during the design stage or measured in the erected building. The physical single number quantities could be the weighted airborne and impact sound insulation as described by the international standard EN ISO 717. Other single number quantities could be considered as well.

However, assessing the reaction of occupants to noise in their homes is a complex task to accomplish. Such reactions are often influenced by factors other than the sound exposure. The other factors can include the occupants expectations, satisfaction, sensitivity and attitude to noise. Hence, such factors may be expected to influence individual answers given in a questionnaire. There are some studies where researchers have tried to take such effects into account (e.g. the "Genlyd" project made at the DELTA institute in Denmark 2004-2007). Furthermore, reactions to noise can be affected by a presence of several simultaneous sources of noise, e.g. exposure to noise from several types of traffic may increase the overall annoyance compared to exposure from one source at a time.

The underlying intention of the questionnaire presented by WG 2 is to determine the average annoyance of the occupants in a building and to relate an average value to the physical property of the building, e.g. the average annoyance from traffic noise (heard indoors) with the sound insulation of the façade. The questionnaire is not intended to reveal causes of subjective responses by individuals to noise in buildings. Furthermore, the questionnaire was written so as to minimise the possibility of unreliable interpretations of terminology or label or scale errors, bearing in mind it should be used in many countries. For this purpose, it was decided at an early stage that the questionnaire template, a cover letter and some instructions to the survey should be written in a kind of simplified "Euro-English" in order to facilitate the translations into a variety of European languages as translated by the WG 2 members, including even a UK English version.

The summary of the questionnaire presented in this chapter is based on a student project report made by F J Andrés Gallego from the University of Valladolid (Spain) during his COST short term scientific mission (STSM) in 2010 at Simmons akustik & utveckling in Gothenburg, Sweden. However, the first draft of the questionnaire which was presented in 2010 has since been revised several times to reflect the lessons learned from surveys which were conducted in the participating countries. For this reason, the STSM-report by Gallego has been slightly modified by C Simmons and members of WG 2. The reasons for the changes have been described and a list of the surveys made since 2010 has been included.

It should be kept in mind that the COST TU0901 questionnaire template has been developed within a collective process that was more in line with standardization work than purely scientific work. Therefore, the questionnaire template is based on several scientific publications as well as practical experiences. Many compromises have been made in the process and the final result is based on the contributions of several people whose work is gratefully acknowledged.

This report provides descriptions and comments made during the stages of development of the socio-acoustic survey questionnaire. The questionnaire has been designed to obtain averaged responses by the occupants of buildings for the purpose of correlating those responses to various types of single number quantity related to airborne sound insulation, impact sound insulation, service equipment sound and traffic sound. Measurements would be used to determine the physical parameters, or in some cases predicted values from theoretical calculations.

The various means of perceiving noise, alternative response terminologies and ratings scales, the effects of wording questions, the use of filter questions, the order of questions and the segments of the questionnaire have all been considered. In some supplementary parts of the template, the means of obtaining building data and acoustic building measurements are described for the purpose of correlating these to the subjective ratings given by the occupants.

While a range of international standards defining measurements of noise, vibrations and other environmental measures are readily available, there are presently no standards or common methods for measuring people's ratings of the protection against noise although many types of questionnaires have been used in Europe. The lack of standards and common methods makes it almost impossible to compare results from different studies and different countries.

Therefore the socio-acoustic survey questionnaire template presented may be a first step to establish a standardised way of assessing occupants' rating of their dwellings with respect to noise sources, e.g. neighbouring apartments, building service equipment, and traffic noise. The design of interior walls and floors as well as facades may differ between the European countries, but the methods to describe the physical performances of the building elements and the method of surveying the occupants to determine their impression of the sound and impact insulation the elements provide should be harmonized.

6.2. Scope

The main purposes of a harmonized questionnaire and its application to socio-acoustic surveys are:

1. To make survey results among occupants from different studies more comparable within or between countries.
2. To deduce the best correlation between the subjective ratings by occupants of the sound levels and sound insulation of their dwellings and to compare these ratings to the various physical single number quantities that describe the acoustic performance of the building.

6.3. Field of application

The questionnaire is intended for socio-acoustic surveys where objective data on the acoustic performance of buildings and service equipment are collected and correlated to the subjective rating by the occupants in order to establish target values for physical single number quantities that reflect the quality goal of a builder, e.g. «not more than 10% should be annoyed by noise more than occasionally».

The institute undertaking the survey shall either collect measured sound data, use generic data of constructions developed by WG 1, or estimate data based on the building constructions and service equipment prior to the enquiry. This step is essential since all questions in the template that are not relevant for a particular site shall be blocked and painted with a grey shadow. This is to still show the occupants that such questions are considered in general cases but the institute performing that specific survey is aware that they are irrelevant in the specific building. For instance, questions about traffic noise or noise from air conditioning shall be blocked if such sources are not present at the site. The numbering and order of questions shall not be changed if individual questions are blocked out.

The principal quantity used to rate the performances is «the annoyance of noise». It has been considered to ask the occupants for their opinions on «how satisfied are you with the sound insulation». However, such approaches were discarded during the development process. One reason the approach was discarded was that the question was difficult to translate into some languages. Another reason was the recommendations of the ISO technical specification ISO/TS 15666 which has influenced the design of the questionnaire to a large extent.

6.3.1. Limitations

The questionnaire is not intended for broad prevalence surveys to characterize the general degree of annoyance from noise in the population of a city or a country. This questionnaire is also not intended for social surveys where no building data is available. It is also not suited to predict annoyance by individuals. Rather, the survey is only applicable for determining the average rating given by a large population of occupants of dwellings in multi-storey houses or attached row houses. Questions about traffic noise or noise from service equipment may be relevant to occupants of single-family housing, but in such cases, questions about noise from neighbours should be blocked.

This questionnaire should not be amended by more questions, e.g. related to other environmental factors or customer satisfactions. Doing so will change the meaning of the questions, potentially giving different results and introducing errors. To keep the questionnaire within one A4-page proved an important property to obtain a high response rate. This is because questionnaires that span over many pages may tire the respondents and therefore, may reduce the response rate as well as the quality of the answers submitted.

The questionnaire is not intended for research on annoyance from traffic noise outdoors. There are other questionnaires designed for this purpose. The questions on façade insulation are only included to assess whether the occupant judge the performance of the building elements (wall, window, air inlet etcetera) appropriate with respect to the sound insulation of the dwelling.

This questionnaire is not intended for assessing neighbours behaviour. The only purpose of the questionnaire is to evaluate the acoustics conditions of the dwellings in a broad sense.

This questionnaire doesn´t make a difference between day and night annoyances but it asks for working times. Therefore, provided the number of responses is large enough to allow for subsets of responses, the response of the could be sorted into different categories.

There are many other factors that are not taken into account, e.g. type of ownership, personal situations, etcetera. Any specific factor may be researched if several studies are performed in parallel, while all other factors are randomized.

6.3.2. Recommendations for translations

The questionnaire should be translated with the intention of keeping the meaning and the wording in the new language the same as the original in the Euro-English template. It is recommended to reference the standard, ISO/TS 15666 as it includes translations in many languages of the main questions of the questionnaire. Particular attention should be paid to the words which replace "bothered, disturbed or annoyed by".

It is not recommended to include any other words in the scale except the extremes, as has been done in the questionnaire template. Introducing an intermediate word in the numerical scale does not facilitate occupant answers, but rather confuses the occupants [5,17]. Furthermore, these intermediate terms are more difficult to translate than the extremes. This is discussed further in the following sections.

The numbering and order of questions shall not be changed and the layout shall be maintained. Only changes necessary for the translated texts to fit on one page should be made [7, 18, 25].

6.4. Terms used during the development

In order to facilitate translations and interpretation, this section provides definitions to describe the intended meaning of the wording in the questionnaire template. These definitions are not applicable outside of this context and not all of them are used in the questionnaire.

Socio-acoustic survey

Surveys designed to measure an average rating by occupants of noise in buildings to establish statistical relationships to physical parameters, e.g. the measured sound insulation as defined in EN ISO 140. The noise may come from interior sources (neighbours, equipment) or traffic noise heard indoors (through windows).

The main characteristic of socio-acoustic surveys when compared with social surveys is that they provide information about the actual building performances and sound levels that pertain to the group of dwellings as have been rated by their occupants.

Social survey

General surveys of living conditions or broader environmental studies where responses are not usually linked to objective measures of noise exposure [16].

Noise

Unwanted sound from specific sources in the building or its outside, as described by measured or calculated single number quantities. [4]

Tolerance

In this context tolerance is defined as the act or capacity of enduring to noise. In other words it is the "sensitivity to annoyance from noises" or the risk of annoyance when hearing sounds.

Tolerable noise

Noise that seems not to bother occupants too much. For example, broadband and stable sounds at low levels from remote traffic, heating and ventilation, without any tones or impulses [20].

Intolerable noise

Noise that seems to bother or annoy occupants, possibly because the levels are too high or the character of the sound is unpleasant, e.g. from the usage of a WC, flushing water through the sewage water pipes, tonal and impulsive noise from an elevator as well as a laundry machine [20].

Noise-induced annoyance: a person's individual adverse reaction

The reaction may be referred to in various ways, including for example, dissatisfaction, bother, annoyance, and disturbance due to noise.

Global annoyance

The accumulated specific annoyance integrated over a range of contexts and over a range of locations at home (e.g. at the balcony, in the kitchen, in the bedroom) [4].

Specific annoyance

Accumulated specific annoyance: The annoyance for a specified stimulus in a specified context for specified persons integrated over time and experiences.

The accumulated specific annoyance is the immediate annoyance and the connected experiences integrated over time, i.e:

- Conversations inside a home affected by traffic noise
- Working next to a noisy printer
- Neighbour usually rehearses drums every evening [7]

Immediate annoyance: The annoyance for a specified stimulus in a specified context for specified persons when the noise actually is present during or immediately before the evaluation of that particular noise. Immediate annoyance may be relevant for the following examples:

- Aircraft passing while you are talking in a phone
- Passing a pneumatic drill on the pavement
- Irrelevant speech while you are working in an office

Noise Annoyance

An emotional and attitudinal reaction from a person exposed to noise in a given context [7].

Noise sensitivity

The degree of susceptibility to noise. According to several authors [21, 26] there are two different concepts of noise sensitivity:

- *Sensitivity to loud noises*: susceptibility to very loud sounds in the distance such as traffic or construction noise.
- *Sensitivity to situations of distraction*: susceptibility to lower, but disturbing, sounds from the direct vicinity such as rustling paper in the cinema or people talking in the background while watching TV (daily disturbances or sensitivity to noise).

Annoyance question

Question or questions with or without filter questions utilized for eliciting people's annoyance to sounds including the response that the sounds are not noticeable [16].

Filter questions

Could be used to determine the respondents who are affected by hearing noise and to measuring their reaction. However, filter questions have been avoided in the questionnaire template because they lengthen the time to complete the survey [16].

Behaviour

The actions or reactions of any person while making or receiving noise.

Modifying factors

Factors that influence the relationship between exposure and effect [16].

Such factors can be

-*external* - such as the presence of additional environmental problems, smells, air pollutions, visual impact in general, visibility of source from home, size of the source, vibrations, location of the dwelling, home ownership, sound scape, etcetera.

-*internal* - such as the degree of sensitivity to noise, expectation, attitude to source, perceived health risks, etcetera.

Exposure-effect relationships

Describe the proportion of people who report or experience an effect at different values or intervals of the chosen noise exposure measure. Exposure-effect relationships may also be described statistically by means of the estimated relationship between an exposure and an effect based on a stochastic model.

Expectations

What is considered the most likely to happen. In this context the hope of having a home with good airborne and impact insulation and the hope of living in a good area, good apartment as the interviewed expected. According to the Genlyd project, there are three types of expectations: Expectation about acoustic quality, about the noise duration and about the increase in the noise level.

Satisfaction

Confident acceptance of something as satisfactory, dependable, true, etcetera. It has been determined that questions regarding satisfaction were not as direct as questions regarding annoyance. Therefore, they could be used to infer the quality of the rating, in particular for noise from equipment or traffic. Questions about satisfaction were considered for use about the sound insulation but were discarded after some considerations within the WG 2.

Attitude to source

The attitude to the sound source may be seen as a number of reasons that may moderate the rating people give to the noise. Several reasons could be grouped under one common factor called attitude. Personal attitudinal factors like attitude to the specific sound source in the specific neighbourhood (Do I want it here?), feeling that the noise annoyance is preventable, did we have influence on the planning process, etcetera [7].

6.5. Question wording

Selecting the wording of the questions used for a questionnaire is a delicate task. There are many factors that influence how the respondents (the occupants) understand the questions, in particular when the questions are to be translated into many languages. The type of, relative weights of, and the optional answers presented are also important to consider. In every word, the way of asking, the type of question and its context introduces a bias error to the answer. This is why it is strongly recommended not to change the questions of the sample questionnaire or the rating scale and to preserve the meaning of the template as much as possible in the translations.

In this work, different ways of wording questions and types of questions were analyzed and it was concluded that are three categories of wordings for question and answers.

- **Hear / notice questions** - An objective question used for detecting noise through partition walls and used as a filter question before the annoyance or assessment question. Rating Scale: Yes/No, or asking to select the sources you can notice or hear through a wall or a floor, etcetera [16, 22].
- **Annoyance questions** - ISO/TS 15666 was published, many questionnaires have followed the guidance of the standard to be able to make relations

with other surveys. Many of the traffic noise and vibration surveys have followed the guidance of the standard. Quantifying annoyance is indispensable for two tasks: to identify individual levels of noise impacts and to operationalize the noise problem for populations (e.g., "% highly annoyed" in the vicinity of an airport) [17]. It is a subjective question. Rating Scale: Neutral to negative (unipolar) [4, 7, 16].

- **Assessment or satisfaction questions** - A subjective question but more objective than annoyance question to assess, evaluate, or to rate the insulation or the acoustics qualities of an apartments or dwelling. Rating Scale: Positive to negative and neutral to positive [1, 12]. This type of questions is further commented in section 10.

The questions should use the right words to receive the most appropriate answers to describe responses and the effects of noise from occupants. The language barrier and the translations play an important role in exporting and importing data from other surveys and this should be taken into account in the selection of the terminology of the questions and the responses scales in the questionnaire.

Some surveys [18] have used combinations of words to cover a wide range of meanings and to be able to establish comparisons. For example, annoyance or disturbance used in the same question allows for comparison of data against surveys conducted in other languages since the meanings of words may be different in those other languages. Therefore, introducing several words makes it possible to cover a wide range of surveys and questions.

What is the best wording or how to assess subjective responses to noise in residential building? The authors are convinced annoyance is the primary indicator to noise *for the purpose of this questionnaire*, making a great effort in research and development of questions and their influence on the results [4,7]. The satisfaction or neutral assessment of the acoustic conditions has some advantages, c.f. section 10 of this report. The assessments begin to be more common especially in the surveys conducted indoors and in new buildings [1]. However, one of the main reasons why the authors opted for the use of annoyance as an indicator is the ease of comparison with other reports and studies which allows for the calibration of the template questionnaire. Another reason is the ease of making translations.

The remaining terminology used in the question took into account other factors such as the period of time in the question (It is not the same to ask for a period of 12 months than a shorter or longer period), the place the occupant is asked about, (in his house, , balcony, garden...), and finally what type of noise sources are involved. Finally, the importance of the verbal time (present) and the use of "you", asking directly to the interviewed [4] has also been taken into account.

The model question proposed in this study follows the pattern of questions developed by the standard, ISO/TS 15666 [4] where the influence of those factors is studied. As a result, the following question wording was included in this questionnaire*:

The right period of time:	"Thinking about the last 12 months when
Person or family reaction asked for:	you are, your family are
Place:	here at home, in your neighbourhood, outdoors
Answer to choose for a degree of response:	how much
General noise:	does noise,
Specific noise source:	from (name of the source)
Wording for assessing the degree of annoyance:	annoy, disturb, bother
Person evaluation the question:	you"

See reference [4]

* Question used in the questionnaire: "Thinking about the last (12 months or so), when you are here at home, how much does noise from (noise source) bother, disturb or annoy you?"

6.6. Type of questions

There are four types of questions: the direct rating question, the indirect and comparison questions, and the indirect question via statement. The direct question has been almost universally accepted as the primary measure of relationship between noise and respondent´s subjective reactions. Answers to such direct questions are more explicit and more readily interpreted than indirect questions or comparison questions [4]. Indirect and comparison questions have not supplemented the direct question as the primary indicators of noise impact because they can only be used to infer indirectly how people feel about noise.

Direct questions are the most commonly used in noise surveys questionnaires. Although the use of direct questions can lead to good results since they explain clearly what you are asking for, so there is not too much wide range of interpretations, the direct questions introduce an error due to inducing people to chose an answer. This questionnaire follows the ISO/TS 15666 recommendation and makes use of the direct question.

6.7. Rating Scales

Two main scales have been considered in the course of developing the questionnaire template: verbal/categorical and numerical scales. During the preliminary stage of collecting information where several studies were evaluated, it was found that most of these studies recommended the use of a verbal scale against a numerical scale or a combination of both to ensure the accuracy of results [4, 7, 16, 17]. The protocol used to choose the words used for the answer scale attempts to ensure that the commonly understood meaning of the word is consistent with its position on the scale [4, 16]. The verbal scale is needed for the clearest, most transparent communication. The simple task of choosing a word is most likely to be easily performed by respondents of any degree of sophistication and in any culture. Other advantages are the easy understanding and the familiarity with the words, assuming most people prefer verbal scales and it also facilitates to capture normative judgments [17].

The disadvantages of using the verbal scale are determined by using the most appropriate terms and the standard deviation introduced by it [5, 17] as shown in Table 6.1. Not all the words used have the same meaning and there is not necessarily the same distance between the categories the words are compared with a numerical scale as shown in Figure 6.1. Also, multi-lingual translations of words with ambiguous meanings are difficult and since this questionnaire is intended to be used in many languages, it was considered an advantage to use as few words as possible.

There are some cultural factors that might confound the data, and most important, cross national and international comparability makes it difficult due to the meaning of the words in different countries. Not all words have the same proximity on the scale, in particular in the middle part of the scale. So, to take an example, if we consider using the five terms [17] "not-at-all", "slightly", "moderately", "very" and "extremely", they may appear a reasonable solution for a verbal scale. However, evaluating this trial scale, shows that there is a rather large gap between level "3" and "4", so the distance between 3 and 4 may be different than the separations between 1 and 2, resulting in a scale with terms that are not equidistant. Several authors have tried to determine the best translations in different languages for a verbal scale and the best equidistant terms by introducing mathematical factors, but there are still difficulties and further research is needed. This problem is explained in the document "On the Meaning of Noise Annoyance Modifiers: A Fuzzy Set Theoretical Approach" [5] where a five point verbal scale is deducted as the most accurate in several languages thanks to the mathematical model applied, as shown in Table 6.2.

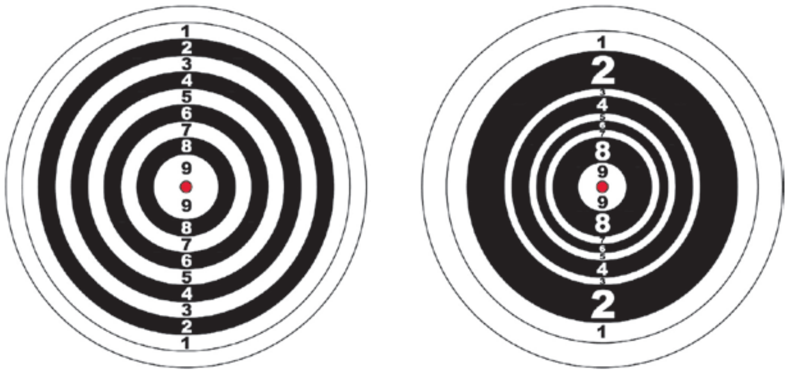
Table 6.1. *Scaling Verbal Qualifiers: selected results for "Intensity". B. Rohrmann.*

Scaling task	Categorial (0...10 scale)				Magnitude <#>		Prefered Label (% respondents) for annoyance scale level					Familiaty	
Context	Noise		All		All							Noise	
	M	sd	M	sd	M	sd	1	2	3	4	5	M	sd
Verbal label													
a little	2.5	1.3	2.5	1.4	10	17		13				7.1	2.7
average	4.7	1.0	4.8	0.9					28			8.8	1.0
completely	9.8	0.6	9.7	0.8	81	161					40	8.5	1.6
considerably	7.5	1.2	7.6	1.1	57	129				21		6.3	1.7
extremely	9.6	0.6	9.6	0.8	76	145					47	8.3	1.4
faily	5.1	1.3	5.4	1.4	46	113						6.4	1.8
fully	9.2	1.2	9.3	1.3	78	161							
hardly	1.6	1.4	1.7	1.2	9	17		18				7.1	1.8
highly	8.6	0.7	8.6	0.9	68	130						7.4	2.1
mainly	6.4	1.1	6.1	1.4	58	129				18		7.4	1.6
medium	4.8	0.8	4.9	0.8					25			7.3	2.3
moderately	4.9	1.3	5.1	1.1	43	112			37			6.5	2.0
not	0.4	0.5	0.5	0.9	2	3	17					9.4	1.0
not at all	0.1	0.4	0.2	1.0	1	0	70					9.1	1.5
partly	3.5	1.4	3.8	1.4	21	49		14				7.0	1.8
quite	6.1	1.5	5.9	1.5	38	81						6.5	2.4
quite a bit	6.4	1.7	6.5	1.6	45	97							
rather	5.9	1.7	5.8	1.6	46	113						5.7	2.3
slightly	2.5	1.4	2.3	1.5	12	17		27				6.9	1.8
somewhat	4.3	1.7	4.5	1.7	27	49						5.3	2.7
very	8.0	0.9	7.9	0.9	63	129				16		9.2	0.8
very much	8.7	0.7	8.6	1.0	71	145						8.7	1.5

The results indicate:

- for some of the tested VSPLs people differ considerably in their allocation of pertinent intensity levels - see items with high standard deviation sd;
- no significant differences between ratings of context-bound (noise) and context-free presented VSPLs;
- rank order of main VPSLs very similar in CAT, MAG-N and MAG-L scaling results;
- when selecting VSPLs for to-be-labelled 5-point scales, most respondents prefer extreme labels at the end (levels "1" and "5");
- most VSPLs are rated as familiar and easy to understand.

Source: Project VQS, ROHRMANN 1998



Perception of occupants of a numerical Scale

Perception of occupants of a verbal Scale translated to a numerical.

Figure 6.1. *Illustration of the meaning of a numerical scale and a verbal scale from the point of view of how occupants. Wording can make some words appear more important and with more weight than the others, distorting the real meaning of each number or word. Also reducing or increasing the gaps between words may play a role.*

Table 6.2. *Best match with the 5 fuzzy ideal labels in each of the languages considered. Source D. Botteldooren.*

	label 1	label 2	label 3	label 4	label 5
German	nicht	**etwas,** teilweise	**mittelmäßig**	beträchtlich, besonders, stark	völlig
Enlish	insignificantly	**slightly,** partially	**moderately**	very, **strongly**	**extremely**
French	pas	**légèrement**	**moyennement**	**beaucoup**	énormément
Japanese	Hotondo..nai	Amari, .nai, Taishite ..nai, Sorehodo ..nai	Yaya, **Tashou,** Hikakuteki, Warini	**Daibu**	**Hijooni**
Spanish	insignificantemente	un poco, algo, un tanto	**medianamente**	**muy,** altamente	**extremadamente**
Turkish	degil	hafifce, birazcik, bir miktar, **biraz,** az cok	**orta derecede**	epeyce, cok fazla	**feci sekilde**
Norwegian	minimalt	noe	**middels**	**mye**	alvorlig
Hungarian	**egyáltalán nem,** nem, alig	mérsékelten	**közepesen**	**nagyonna**	**rettenetesen**
Dutch	niet	iets, lichtelijk, **een beetje,** enigzins, matig	matig, **tamelijk,** behoorlijk	**erg,** sterk	**extreem**

The disadvantages of the verbal scale are why a numerical scale was used for the questionnaire template. The questionnaire template uses an 11-point (0-10) numerical scale (even if a 1-to-10 scale would be more readily understood and treated statistically. Shorter 7-point scales are sometimes used [4, 7]). As shown in Table 6.3, an explanation of the meaning of the scale appears in the header of the questionnaire to allow for the determination of the proper use of extremes and their meaning in the analysis of the results. The familiarity with this scale in different countries (most occupants are familiar with base-10 numeric systems) and recommendations for international surveys [4, 7, 16, 18] studies, among others factors (easy to convert in % and to analyse it), led to the use of this scale as shown in Figure 6.2.

Table 6.3. *Instructions for completing the scale of the questionnaire.*

<table>
<tr><td colspan="4">Instructions:
Choose an answer on the 0-to-10 scale for how much noise bothers, disturbs or annoys you when you are here at home.-</td></tr>
<tr><td>if you hear the noise but you are not disturbed by it,
choose 0</td><td>if you are extremely bothered, disturbed or annoyed by it,
choose 10</td><td>if you are somewhere in between,
choose a number from 1 to 9</td><td>if you do not hear anything at all, the source does not exist or it is not possible to answer,
choose "?"</td></tr>
</table>


Not at all										Extremely
0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Figure 6.2. *Instructions for completing the scale of the questionnaire.*

The scale uses both verbal descriptions (texts) and graphical emoticons in the extremes in order to remind the occupants of the meaning of the scale and to make respondents see the simple use of it. In the expectations and sensitivity segments, the wording in the extremes is reinforced by adding "important" and "sensitivity" so as to show the question scale asses their personal reactions to noise.

6.8. Sources list

One of the most important characteristics of the questionnaire is that respondents are not asked to determine which sources of noise they hear in their buildings, resulting in a shorter survey. This is advantageous since irrelevant questions should be avoided. Those giving the survey can determine what are the most annoying sources in each type of dwelling through other studies or personal or cultural experiences.

Each subjective response and each source of noise may be correlated to one or several physical parameters, e.g. of airborne and impact sound insulation. Different studies [11, 24] show an increase in discomfort by certain sources of noise on occupants and give a list of the most heard noise sources and most annoying. In these lists it is found that most countries have the same sources of noise and almost the same most annoying sources (loud conversations, music, walking heavily on floors, etcetera). So the questionnaire asks about the most common noise sources which will be correlated with the airborne or impact sound descriptors. However, in the course of translation the questionnaire, considerations could be taken to whether more typical sources of noise should be included or less common sources should be excluded.

The next list is the sources most commonly heard perceived as annoying asked as based on a questionnaire by TNO, National Survey Study as shown in Figure 6 and based on personal experiences on the field.

Table 6.4. *Table most heard sources in a building listed by TNO and UK National Survey Studio.*

ANNOYANCE (priority list)	
Netherlands, TNO Study	UK, "*National Survey of Attitudes to environmental Noise*"
1. Playing special pop music	1. Teenagers' or adults' voices Speaking
2. Noise from TV/radio/audio turned up loud	2. Radio, TV, music
3. Slamming of doors	3. Dogs
4. Sounds from spin drier or washing machine	4. Children
5. Walking heavily on floors	5. Cars/motorcycles starting up/leaving, repairs etcetera.
6. Walking heavily on stairs	6. Burglar alarms
7. Do it yourself (DIY) sounds	7. DIY (hammering, drilling, etcetera)
8. Speaking with raised voices or shouting	8. Doors banging
9. Dog barking	9. Lawnmowers or other garden equipment
10. Flushing sounds from toilet	10. Parties (when held outdoors)
11. Noise from TV/radio/audio at normal volume	11. Parties (when held indoors)
12. Noise of showering and/or taking bath	12. Footsteps
13. Normal" walking on staircase	13. Domestic equipment
14. Sounds from spin drier or washing machine	14. Other animals
15. Speaking normally	15. Electric Switches
	16. Any other kind of noise b (flushing toilets, mobile phones, etcetera)

6.9. Segments of the questionnaire

Section 6.9 is omitted in this printed version but is fully available in corresponding the e-book

The questionnaire template has been designed to keep the number of questions as small as possible and address the most important sources of noise inside dwellings. Sources were taken from other studies [10, 12, 16, 18, 22, 23]. The questionnaire also makes a distinction between airborne noise transmitted through walls and floors and the noise produced by footfalls, vibrations and etcetera.

The process of selecting the most important questions for this questionnaire started from the analysis of surveys and their segments. For the design of the segments of this questionnaire a draft questionnaire was created including all the questions used in other surveys, resulting in a total of 70 questions. The question were then reviewed to determine which segments and which questions were the most relevant for the purpose of a socio-acoustic intended to determine whether building constructions offered appropriate sound insulation and attenuation from noisy equipment.

After a long discussion and a period of analyses, questions and segments were eliminated one by one so that the most relevant items were focused on and the number pages was reduced to one, thus reducing the time for completing the questionnaire [See process of questionnaire developed in paragraph 5.1.1.]. It is believed that the process of reducing the questionnaire to one page has helped to obtain a satisfying response rate, often better than 70%.

Segments of the questionnaire:

1. Introduction and personal data: The introduction explain the purpose of the questionnaire and how to rate the answers. The main page contains the address and contact data of the survey institute which will carry out the survey. The introduction is clearly readable. This part also includes questions regarding personal data of the person filling out the questionnaire as shown in Figure 6.3 such as age, gender, years of residence number of persons in the household, etcetera.

2. Instructions: The instructions explain how to fill the questionnaire and the meaning of the extremes of the scale. Several ways of filling the questionnaire were developed. To try to avoid having an extra column, several options were taken into account such as "make a line through the

Investigation - purpose
[*THE INSTITUTE*] has been commissioned by [*THE COMMISSIONER / AUTHORITY*] to research whether residential buildings have satisfactory noise conditions. Several buildings have been selected randomly for the survey and this one was included. Your responses help us define appropriate requirements in the building regulations. The requirements must prevent poor constructions being adopted but also enable cost efficient constructions to be use. Too high requirements would lead to unnecessary costs. For this reason, it is important to ask occupants about their opinions and check whether the noise conditions are satisfactory. We thank you for taking your time to fill in this enquiry. Your responses will be treated statistically and confidentially at all times. The results and your personal data are only used for this research.
Please leave your form in the [DELIVERY PLACE IN HOUSE XXX]. In case you would like to submit your answers on the internet, visit our information site www.[SURVEY-WEBSITE].cc If have any questions or prefer to answer by telephone call our Help Desk: +cc xxx yyy zzz e-mail to enquiry@[INSTITUTE-CONTACT].cc visit www.[SURVEY-INFO-WEBSITE].cc Thank you for your cooperation! [Name of responsible part for the enquiry] [Institute]

YOUR PERSONAL DATA [Filled in by the respondent] . N.B! [THESE DATA ARE ONLY FOR THIS SURVEY AND WILL BE DELETED AFTER ITS ANALYSIS]					
Gender:	F: ☐	M: ☐			
Age:	18-25 ☐	26-39 ☐	40-64 ☐	>65 ☐	
Working schedule:	Day ☐	Evening/night ☐	Mixed ☐	Not applicable ☐	
Years of residence:	0-1 ☐	2-5 ☐	6- ☐		
N° of person in the household:	1 ☐	2 ☐	3 ☐	4-6 ☐	6- ☐

Figure 6.3. *Introduction and personal data.*

question in case you do not hear anything or does not exist". In the end, it was observed that respondents often could not remember an answer so a column was introduced and it was labelled with N/A and a "?" to the right of the numerical scale as shown in Table 6.3.

3. Introductory example: An example explaining how to fill the boxes of the scale is added in order to show the methodology of the questionnaire. It is explained that if a mistake is made, "If you already marked out one box but you want to change your answer, fill the box in black and mark a new X in the new box". Also the position of the main question, the scale and the N/ A column is marked as shown in Figure 6.4.

4. General question. This question is a question recommended by various authors [Truls Gjestland and 4, 7,17] to calibrate the survey with other surveys and as a training question for the respondents because it is the first question and the first time they will rate using the scale. The general question asks about general noise annoyance, not specifying in detail the type of sources of noise trying to be general (neighbour noises, and technical installations etcetera). It does not specify either if the respondent is inside or outside his/her home, so it will allow comparing with the next segment where the questions clearly specify it is indoors, figure 6.4.

Thinking about the last 12 months here at home, what number from 0 to 10 best shows ***how much you are bothered, disturbed or annoyed by***	Not at all							Extremely				
	0	1	2	3	4	5	6	7	8	9	10	NA
1. Noise in general e.g. from neighbours, technical installations etcetera	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Figure 6.4. *General question.*

5. Questions on noise generated by different noise sources. This segment contains the main body of the questionnaire. All the sources evaluated were chosen in accordance with prior studies where the priority of hearing and the annoyance of the sources were listed. It was found that most sources are common in the COST member states, so it was decided to ask for the most common sources of noise instead of asking respondents to mark which ones they hear. The answers may be correlated with the sound insulation parameters in the analysis of the results as shown in Figure 6.5.

6. Question about expectations. Among factors that influence the results, expectations was one of the factors considered in some studies but not studied [7]. From the explanation of some documents and personal experience, expectations may play an important role in the answers and these will vary according to respondents' expectations. This segment was included in order to allow for studies regarding the relationship between the answers and the sensitivity. It is possible that fitting the annoyance answers could later be made and the slope of the dose-response curve adjusted accordingly. The question shown in Figure 6.6, is designed to focus on the expectations to the acoustic quality rather than asking about the expectation of duration time of the noise source or expectation concerning the increase of the noise level.

Thinking about the last 12 months here at home, what number from 0 to 10 best shows how much you are bothered, disturbed or annoyed by ***these sources of noise?***	**Not at all**							**Extremely**				
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**NA**
1. Neighbours; daily living, e.g. people talking, audio, TV through the walls	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
2. Neighbours; daily living, e.g. people talking, audio, TV through the floor / ceiling	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
3. Neighbours; Music with bass and drums	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
4. Neighbours; footstep noise, i.e. people walking on the floor	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
5. Neighbours; rattling or tinkling noise from your own furniture when neighbours walk on the floor above you	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
6. Climate installations; heaters, air condition, air terminal …… continued	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Figure 6.5. *Annoyance questions segment.*

Before moving to the apartment, what number from 0 to 10 best shows ***how important the sound insulation was to you, with respect to***	**Not at all important**										**Extremely important**
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1. Noise in general e.g. from neighbours, technical installations etcetera	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Figure 6.6. *Expectations question.*

7. Question about sensitivity. This section contains one of the most important factors which influence in the answers. From all the types of sensitivity questions [7, 21] the questionnaire asks a direct question about if the respondent considers him/herself sensitive to noise as shown in Figure 6.7. It is an inducing question but it is important to know the personal reaction to this question in order to know if the rest of the answers are affected by the respondent's sensitivity to noise.

8. Comments section: The occupants may describe in own words, what is important concerning annoyance, e.g. which source(s) of sound are disturbing them.

How sensitive are you to	**Not at all sensitive**										**Extremely sensitive**
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1. Noise in general e.g. from neighbours, technical installations etcetera	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Figure 6.7. *Sensitivity question.*

9. Notes of application. These notes are to be used by the surveying institute and will not be included in the questionnaire format. The notes may include considerations and recommendations for achieving all the purposes of the survey. Also the recommended survey procedure is explained for the survey institute.

(Note: this section is slightly different in the final version of the questionnaire)

Questionnaire application Notes to the Institute

This questionnaire is intended for socio-acoustic surveys, where objective (physical) data on the acoustic performance of buildings and service equipment are correlated to the subjective evaluation by the occupants, in order to establish dose-response relationships. Annoyance is chosen as the measurand according to ISO/TS 15666 since it has proved to reduce the scatter of responses, although the type of question may lead to an apparent over-estimation of the general annoyance. In the course of developing this questionnaire, less inducing questions were considered, but the ISO/TS 15666 question was finally thought to be the best choice for the purpose. The questionnaire is not intended for broad prevalence surveys to characterize the general degree of annoyance from noise in the population of a city or a country, nor its effects on health etcetera.

The questionnaire is not intended for research on annoyance from traffic noise outdoors. There are other questionnaires designed for this purpose. The question on façade insulation are only included to assess whether the occupant judge the building elements (wall, window, air inlet, etcetera.) appropriate with respect to their sound insulations.

This questionnaire is not intended to assess the neighbours behaviour. The only purpose of the questionnaire is to evaluate the acoustics conditions of the dwellings.

The numbering and order of questions shall not be changed and the layout shall be maintained. Only changes necessary for the translated texts to fit should be made.

The institute shall collect data on the building constructions and service equipment prior to the enquiry. All questions that are not relevant for the *site shall be blocked and painted with a grey shadow. This is to show that such questions are considered in other cases but the institute considers them irrelevant in this specific building.*

Survey procedure:

> *Step 1: Inform the all occupants about a survey being made soon in the house. Explain them the purpose of the survey is research on the building regulations only. Our company [THE HOUSING COMPANY] participates in this survey. You will receive a survey form and an envelope. Please fill in and leave the envelope [DELIVERY PLACE IN HOUSE XXX].*
>
> *Step 2: Distribute the surveys to all the occupants.*
>
> *Step 3: Collect the survey forms.*
>
> *Step 4: Remind respondents twice by post or by one telephone call.*

The institute shall provide instructions to the occupants, including answers to frequently asked questions to the extent judged to be necessary in each case (FAQ).

If the survey is made by telephone the institute shall also provide guidelines for telephone interviewers etera in order to facilitate a smooth and uniform interview. See ISO/TS 15666.

10. Object data. This part will be completed by the institute. It is really important to be able to measure or to know the sound insulation values. For that reason the building data and the building characteristics are required. The survey should include (when possible) the details of the constructions (with dimensions or scaled), plans and drawings to be able to estimate the sound insulation values in the cases where there are no measured data available (using prediction standards and/or specialized software). This is required in order to correlate the subjective answers with the real or estimated objective values.

11. Building data. The building data on page 4 in the questionnaire template is divided in three sections: a) Building site plan information contains the urban plans and the relation between the building and the city and surroundings (influence of external environmental sources, high, proximity airports, etcetera). b) Building equipment contains the general installations of the building like elevators, general heater or water, etcetera and c) Dwelling plan information and dwelling information contains the data needed to classify the dwelling and to make an estimation or calculation of the sound insulation objective parameters. See figure 6.8.

SURVEY INFORMATION Filled in by Survey Institute		
Form Number		
Respondent:		
Country:	City	Postal Code
Adress:		
BUILDING INFORMATION Filled in by Survey Institute (the purpose it is to allow outdoor calculations in case no measurement data or not Urban noise plans)		
Building site plan information		
Wide site plan: shows the situation of the building with respect to the traffic or other sources of noise. (Urban Plan scale1:5.000 or 1:10.000)		
Street building plan situation: shows the relation with the next buildings and with the street. (Plan scale 1:500 or 1:200)		
Street building cross section: shows the size and position of the windows facing the road		
Distance to (km) Highways __ Roads __ Train / Trams __ Bus __ Airport __ Pub Disco / Music Area __ Outdoor area __		
Building equipment		
Individual house heat Heater ☐ Water Heater ☐ Electric Heater ☐ Air conditioner ☐ Cooling unit ☐ None ☐		
Central heating system Heater ☐ Water Heater ☐ Electric Heater ☐ Air conditioner ☐ Cooling unit ☐ None ☐		
Individual Heater/cooling Air handling unit (exterior) ☐ Compressor unit (exterior) ☐ Compressor unit (interior) ☐ Other ☐		
Central cooling units Air handling unit (exterior) ☐ Compressors units (exterior) ☐ Compressor unit (interior) ☐ None ☐		
Central equipment Laundry ☐ Dryer ☐ Other ☐		
Floor premises: Gym ☐ Offices ☐ Schools ☐ Clinic ☐ Other ☐		
Ground floor premises Laundry rooms ☐ Garages ☐ Shops ☐ Offices/Clinic ☐ Restaurants /Pub/Discos ☐ Other ☐		
DWELLING PLAN INFORMATION Filled in by Survey Institute (the purpose is to estimate airborne and impact sound insulation, e.g. according to EN 12354)		
Building floor plan: shows whole floor with the dwelling of the study and all the neighbours apartments (Scale from 1:100 or 1:200)		
Dwelling cross section: shows the rooms' situation and the type of room above and below. (Scale from 1:50 to 1:100)		
Floor detail: shows the materials and the layer used to be able to estimate the insulation. State the thickness (Scale from 1:5 to 1:50)		
Roof detail: shows the materials and the layer used to be able to estimate the insulation. State the thickness (Scale from 1:5 to 1:50)		
Exterior Walls detail: shows the materials and the layers used to be able to estimate the insulation. State the thickness (Scale from 1:5 to 1:50)		
Partition wall detail (separating next apartments): shows the materials and the layer to be able to estimate the insulation. (Scale from 1:5 to 1:50)		
Partition wall detail (separating staircases or corridors): shows the materials and the layer to be able to estimate the insulation. (Scale from 1:5 to 1:50)		
Window glass type: Describe the glass pane		
Window frame type: Wood or Wood/Aluminium ☐ Steel/Aluminium ☐ PVC ☐ **Window seals ok?** Yes ☐ No ☐		
Elevators next to room: Yes ☐ No ☐		
Central Staircases: Yes ☐ No ☐ **Staircase structure:** Light (steel, wood...) ☐ Heavy (Concrete) ☐		
OTHER DWELLING INFORMATION Filled in by Survey Institute		
House type: Detached house ☐ Terraced housing ☐ Apartment ☐ Villa ☐		
Apartment / Loft Floor: Basement ☐ Intermediate ☐ Floor N° __ N of rooms: ___		
Type of Ownership: Rental ☐ Membership or Self owned ☐		
Extras: Quiet balcony ☐ Access to quiet Outdoor area ☐ Own garden ☐		
N° Apartments per floor: _____		
Apartments above floor: Yes ☐ No ☐		

Figure 6.8. *Building - dwelling data.*

6.10. Sampling

The primary aim of the sampling procedure in socio-acoustics surveys designed for establishing relationships between measured data and occupants' ratings is to capture a representative sample of occupants. In many cases, all occupants within a block of buildings can be invited, which is advantageous from a statistical point of view.

Sample selections (by means of a stratified sampling) may be used, if they select the same per cent of people according to age, gender, length of residence and the building age and characteristics for getting and heterogeneous sample which will give a wide range of the acoustic quality of the buildings in each European countries. A more common application is probably within one block of buildings. Results from such limited studies are not representative for the whole population, but may return important information to builders and others. If many such studies are performed, a broader perspective and relevance for national guidelines etcetera may be derived.

This questionnaire could use two criteria for the sampling procedure:

Sample Selection:

- Respondent sample selection method (probability, judgmental, etcetera)
- Respondent exclusion criteria (age, gender, length of residence, etcetera)

Sample Size and quality

- Response rate
- Reasons for non-response

Further discussions on the effect of sampling must be analyzed by a statistician in each application, unless all occupants within a specific area are invited. However, the results are then only representative for this area. If the sampling is sparse, other effects may occur.

6.10.1. Measurements

As already mentioned in the previous section, in order to correlate the occupants' ratings of annoyance with sound insulation values it is important to make measurements "in situ" (and include in the survey the methodology followed, number of measurements and the instrumentation used) or to be able to estimate those values through construction details, building data and traffic noise plans (calculated by computer programs, through laboratory measurement values, etcetera).

There are three main methods available for obtaining the sound insulation values of constructions solutions of dwellings and correlate them with the subjective responses:

1. Measurements "in situ", adequately planned, may describe the properties of the construction solutions and the existing sources of noise. At least 5% of all partitions or rooms should be measured to get at reliable estimate of the building performance, and at least 3 partitions should be included
2. Applying generic data, e.g. from the catalogue established by COST TU0901 WG
3. Estimate the measurements via:

- Acoustic Software: to calculate airborne and impact sound insulations using standardised software (according to Standards)
- Laboratory measurements and tests insulations values of constructions solutions

6.10.2. Analysis of the results

Statistical analyses of responses from the questionnaire can test the reliability of the responses and examine relationships between subjective responses and objective values of sound insulation.

This questionnaire has been applied in surveys and the analysis of the results has been performed mainly using linear regressions. Examples of studies are listed in section 11. Other correlation methods maybe considered as well, e.g. multivariance analyses. There are many other statistical methods which can be used, depending on each type of survey and the way of treating results [1, 2, 12, 18, and 21].

This questionnaire may be used with more advanced statistical methods, since it collects information on age, gender, length of residence, and quality of construction, year of the building etcetera. Simplicity and interpretation of data without complex mathematical operations allows for a faster exchange of information and results, without having to convert scales or analyse complex results. If the survey institute would like to make a classification with clustering or to introduce other changes, then everything should be explained in detail with the survey results as well as the reasons why this has been made.

The results of the blocks of expectations and sensitivity could be used to adjust the slope of the results obtained in the annoyance block, explaining where, why and how these results modify the slope of the curve obtained.

6.11. Updates to the questionnaire after preliminary studies and experiences

Since the first draft of the questionnaire based on the ISO/TS 156664, the UK delegation expressed concerns that the use of terms "annoyed, bothered and disturbed" as the basis of the subjective experience of noise in the home, would cause problems. Some other delegates shared this concern.

In the UK, consumers are accustomed to receiving 'customer feedback' questionnaires every time they buy a new product or use a service. Such questionnaires are invariably of the 'customer satisfaction' format, asking "how satisfied are you with..........". The use of a direct question which asks "how annoyed are you with...." was considered to be likely to provokes a negatively biased response, or even invoke a complaint where none existed.

The first attempts in the UK to 'test' the questionnaire involved asking house-builders, housing associations and building managers if the questionnaire could be circulated to new occupants of homes for which test data was available, both rented and privately owned. Without exception, all such requests were refused.

The UK then proposed two alternative versions of the questionnaire, one which was 'neutral' e.g. asking "how much noise can you hear from......." and a second which was based on 'satisfaction' e.g. "how satisfied are with the level of sound insulation of.....". The latter approach roughly followed the format of previous surveys used in the UK. When the same group of house-builders, housing associations etcetera were consulted, about 30% thought that the 'satisfaction' version would be OK.

However, after much discussion about the alternative approach, it was considered too problematic to have two different questionnaires when the objective of WG2 was to create a single 'harmonised' questionnaire. There were also concerns that some countries might not understand the concept of 'sound insulation'. A decision was therefore made at the Warsaw COST meeting in 2013 to revert to the ISO format questionnaire, i.e. the original draft which was based on annoyance.

The recent version of the questionnaire has been carefully re-worded, however, avoiding the use of the term 'neighbour noise' so as to make it more objective.

One issue which does remain in the UK and will continue to be a barrier to obtaining a response to questions about noise disturbance is the fact that any problem with a property, including a 'noisy neighbour' or 'neighbour noise' problem, has to be declared when the property is sold. Failure to report problems like this can result in serious litigation so people are obviously reluctant to make formal complaints.

To help with this, the introduction to the questionnaire now explains very clearly that the research is solely concerned with the acoustic performance of the building, not the behaviour of neighbours and that the research results are completely confidential. When these facts and goals have been explained, we think it will be easier to convince the UK building industry and building occupants to use the harmonised questionnaire.

It is also noted that the questionnaire has already been translated into several European languages and cultures to enable comparisons across different countries and cultures. These can be found at http://www.costtu0901.eu

6.12. Applications of the questionnaire in field surveys

The questionnaire has been applied in several studies, as has been reported in international conference proceedings. Some examples:

1. The "SBUF" socio-acoustic survey in modern multi-family residential houses with floors and walls made of massive concrete or light framed structures of wood or steel, ref [31]. The number of occupants responding to the survey was in all cases more than 30, in most cases more than 50.
2. The "AkuLite" socio-acoustic survey in modern multi-family residential houses with floors and walls made of wood, ref [32]. The results were used to propose a new single number quantity to the ISO TC 43/SC 2/WG 18 for inclusion in the proposal for a new standard (ISO/NP 16717-2).
3. The "AcuWood"-project by Fraunhofer Institute, presented at Internoise 2013 ref [33, 34]
4. The "ÄKK"-project by Finnish Institute of Occupational Health, ref [35]
5. Small scale tests with the questionnaire have been undertaken in Italy (Pontarollo et al), in the UK (Critchley), Serbia (Sumarac) and Spain (Herráez et al) but these studies have not yet been published.

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7

Developing a Methodology for Performing Listening Tests Related to Building Acoustics

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CHAPTER 7 Developing a Methodology for Performing Listening Tests Related to Building Acoustics

7.1. Introduction

Human capacity to experience taste, smell, touch, colour of light, temperature, or colour of sound is quite remarkable and has been quite thoroughly investigated via perception tests in psychology and medicine with the aim of assessing the human ability to qualitatively and quantitatively discriminate between different levels of observables. Even in marketing, research perception tests are commonly used to determine individual or common trends concerning preferences.

One of the main challenges in building and room acoustics is to assess, by objective descriptors, the acoustic performance of building structures on one hand and the acoustic comfort in building interior on the other hand. In room acoustics, many parameters that express the perception of loudness, reverberation, speech intelligibility, clarity of sound or spaciousness have been established over the years [ISO 3382; IEC 60268-16, ISO 532B, ANSI S3.4 2007]. Besides the quantifiers directly or indirectly based on loudness, other psycho-acoustical parameters have been consolidated into standards as well. Most of them have been developed for the evaluation of stationary sound and they have become quite popular acoustical indicators in the automotive industry and for the assessment of sound produced by machines (Bismark, 1974). However, to what extent these parameters can be used to describe more complex acoustical situations still needs further investigation. Some psycho-acoustical parameters are still under development or in a tuning phase. Other efforts have been dedicated to the perception of sound in concert halls with and without scattering, on disturbing effects of flutter echoes in sports halls, and on various acoustic problems related to stage acoustics. In all cases, listening tests play a key role when drawing conclusions.

In building acoustics, the sound insulation properties of walls, floors and building elements are measured according to international standards (series of ISO 10140) and rated according to (series of ISO 717), the results being expressed as single-number quantities or descriptors being a sum of a single-number quantity and a spectrum adaptation term. A need for revision of requirements for dwellings has increased due to acoustical problems resulting from (1) Increased use of lightweight structures (2) the appearance of new kinds of sound sources in households, with higher sound power, and often also containing strong low frequency components (3) new infrastructures and technical services in buildings that produce more installation noise than before (such as air-conditioning), which are often indicated as very disturbing, not always due to very high sound levels, but because of different tonal components.

Low frequency components in sounds produced by inhabitants of dwellings have uncovered the weak points of recently very popular lightweight constructions. Lightweight walls are typically based on mass-spring-mass systems with typically very high sound insulation values at middle and high frequency ranges, but their modal behaviour below 100 Hz causes the deterioration of sound insulation properties of such building elements (e-book - COST Action FP0702).

Besides the problems of acoustic discomfort due to sound sources originating from neighbours, transmission of sound between neighbouring apartments evokes privacy issues as well. One of the reasons underlying the increasing trend in awareness of non-ideal sound insulation within buildings is the effort to improve thermal and sound insulation properties of external walls. Although in principle a positive evolution, the improved sound insulation of external walls has eliminated the masking effect of rather stationary traffic noise, leading to an enhanced perception of non-stationary, meaningful, and thus more sensitively perceived sounds coming from neighbour's activities.

The question arises, how to evaluate the airborne and impact sound arising from neighbour activities and how to determine the acceptable limits of disturbance. A simple solution for the first step could in many countries be to enhance the value of sound reduction index for walls and floors between apartments by making the limit value stricter and by proposing to extend the frequency range to lower frequencies. However, research by means of listening tests could be very useful for obtaining a more refined vision on the problem and its possible and optimized solutions as the second step. Besides the problems of acoustic discomfort due to sound sources originating from neighbours, transmission of sound between neighbouring apartments evokes privacy issues as well.

High quality auralization and sound reproduction systems in special laboratory conditions, combined with findings from audiology and psychology enables the researchers to perform a variety of listening tests that can help in the development or validation of proposed methods, for deciding about threshold values on parameters for standards and for constructing guidelines in order to reach the desired acoustic comfort in building interior.

7.2. Perception of sound and its interpretation

7.2.1. Hearing and listening

In acoustic terms, hearing and listening is not the same thing. Hearing is one of the five human senses and can be described as the physical process of perception of sound.The human capacity to experience the intensity and colour of sound is quite remarkable. Hearing is the first sense that is developed in a human foetus, already in the 12th week after conception. The ears have not been formed yet at that time, but the foetus is already able to perceive different vibrations and resonances. Hearing is in several ways much more sensitive than eyesight. The dynamic range of the audible magnitudes of sound of a healthy human ear is around 130 dB and the frequency range between 20 – 20000 Hz is about 400 times wider than the visual spectrum from red (405 THz) to violet (790 THz) colour. And, we are able to distinguish more than 1300 tones, but only around 150 colours of light.

Listening is a cognitive process of actively sensing and interpreting, involving both behavioural and cognitive activities (Greene, 1988). Listening comprises short-term and long-term elements, and memory appears to play an important role in the assessment of listening (Bostrom, 1996). Some musicians are even able to imagine pieces of music in such a suggestive way, that the changes in brain are identical to those when real music is played (Gerrig and Zimbardo, 2010).

Sound can also significantly affect our emotions and its perception and interpretation is very complex. The perception and interpretation of what we see or hear is strongly affected by subjectivity and it is still impossible for tools such as artificial intelligence to grasp the meaning of perceived sound in real time or from a recording. Typical for subjective hearing is that there are sounds that we hear consciously, which are in our foreground, and sounds that we hear subconsciously, perceived as a background (Schlittmeier and Hellbruck, 2009).

Great progress has been achieved towards approaching the human ability to recognize speech, but the subjective evaluation of complex information present in sound signals still outperforms artificial recognition tools. In the medical domain, it is still the doctor who interprets the sound of a patient's lungs or heart via a phonendoscope or a stethoscope, rather than computer programs.

Also in room and building acoustics listening tests can help to detect acoustical problems, or to judge the acoustical quality of a scene, and therefore lie on the basis of the development of new parameters that can be obtained by computer-based analysis. In addition, there can be sounds present that have a special meaning for us or for society in general, such as warning signals, church bells or sounds typical for given place, so-called keynote sounds.

7.2.2. Hearing tests and listening tests

There is also a difference between hearing tests and listening tests. The tests performed by audiologists to evaluate the sensitivity of a person's sense of hearing, belongs to one of the typical hearing tests. Listening tests on the other hand represent the important class of perception tests that are chosen according to the nature of the phenomena to be investigated. Listening tests belong to perceptive measurements where the sound is used as a stimulus. In the field of building and room acoustics, listening tests are essential for the conception, verification and selection of objective acoustical parameters that allow us to assess the acoustical situation in buildings in a quantitative and concise way. The conception of a parameter, and/or criteria for drawing conclusions or taking corrective measures, usually requires an iterative and long process, which is quite delicate when e.g. a decisive single number rating is required.

Listening tests may be discriminative (e.g. paired comparison) or descriptive (e.g. semantic differential). In NT Acou 111 (2002-5) two types of listening tests are distinguished: (1) so-called "objective", related to perception of what do the subjects (persons) hear) or (2) so called "subjective (affective)" related to what do the subjects prefer or dislike. In the so-called objective tests, the main purpose is to give information about the character of the sound and in the so-called "affective" tests to give information about people's perceptions of sound in a given context (NT Acou 111, 2002-5).

7.3. Conception of listening tests

A listening test can be seen as a compilation of 4 phases: One starts from an (1) original sound signal, as it is generated by a natural (vocal sound, sound of river or sound producing object such as hammer or footsteps) or artificial (digital or analogue synthesizer) source. The (2) sound is then propagating through the medium between the source and the listener. The effect hereof is that the initial sound signal is convolved with the impulse response of the surrounding space or environment and the (3) Head-Related Transfer Function (HRTF) of the receiver. The environment can be homogenous and therefore relatively simple (if sound is propagating "only" in air), but can be also more complex, in cases where sound is produced in one room, passing through different kinds of obstacles such as wall or floor structures, to be radiated by these structures in a neighbouring room, creating audible changes in air pressure. In these cases modelling or measuring the sound field in sending and receiving room as well as sound propagation through the material is necessary. HRTF can be measured on a real person or on artificial head and can also be simulated by BEM models. Finally, the sound arriving in a person's ears, is processed by the (4) physical and neurological parts of the hearing system. These phases are all interconnected and cannot be seen in isolation (Figure 7.1). This process can be based on measurements or on simulation, followed by "auralization" of the arbitrary sound signal. An auralization has to be understood as a process in which measured or simulated sound field is made audible (Vorländer, 2008).

7.4. Measurement based auralization

In order to keep maximum control over the features of sound stimuli to be used in listening tests, it is important to record the initial sound in anechoic and noise-free conditions, and using a microphone and pre-amplifier with a flat or carefully calibrated frequency response over the whole audible range (ideally 10 Hz till 18 kHz, inferring a sampling frequency typically 44.1 kHz), and with a linear response over a wide dynamic range (ideally 0 dB SPL to 120 dB SPL). This is to ensure that the sound is not influenced by unknown room-acoustic, audio-electronic, or unwanted source aspects.

For binaural auralization, the use of the artificial head is essential. For the listening tests, the microphones of the artificial head need to be placed at the ear entrance rather than the eardrum, in order to avoid the multiplication of the ear channel filtering (once in the artificial head during recording and again by the ear channel of the listener himself) during the

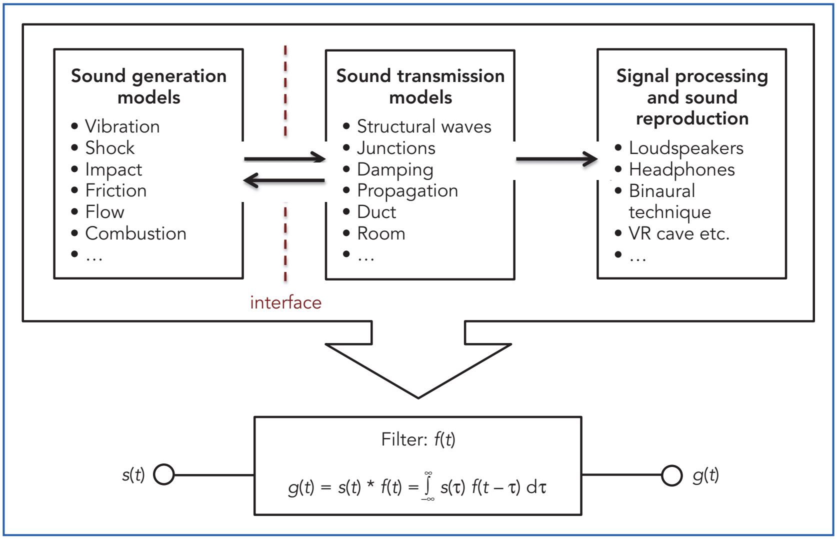

Figure 7.1. *Illustration of the auralization chain, e.g. sound generation, transmission, radiation, signal processing and reproduction (Vorländer 2008).*

listening tests. If the measurements are done by microphones placed at the eardrum, the ear channel influence can still be compensated for, as well as the frequency response of the headphones.

Measurement based auralization in building and room acoustics is accurate, but doesn't allow enough flexibility to perform parameter studies where the influence of a specific feature could be easily and systematically investigated (Jeon et al 2004). Development of the simulation models is therefore of main interest when research studies are going to be based on laboratory listening tests.

Although the research in room acoustics almost always requires stimuli that contain spatial information (e.g. binaural etc), in building acoustics monaural stimuli represents a satisfactory basis in certain cases.

7.5. Prediction models and auralization

In room acoustics, sound propagates in only one medium, i.e. air, which makes prediction somewhat easier in comparison with building acoustics. A partial overview of the state-of-the-art achievements in auralization used in room acoustics is given in (Rindel 2004; Vorländer 2006). Meanwhile, binaural auralization has been also successfully used in audiological research, e.g. in relation to sound source localization (Rychtarikova 2011).

In building acoustic application, more calculations are involved, since the simulation model requires modelling of the sound field in both sending and receiving room, as well as of the sound propagation through the material of the construction separating both rooms. Distinction is also made between airborne sound, impact sound, and sound from installations. Prediction models developed by (Vorländer 2006) have shown sufficient accuracy in 1/3 octave band spectrum useful for research on ratings of sound insulation. The proposed method has been proven to be satisfactory for auralization purposes as well and can be used for investigation of the sound effects, noise and noise annoyance by variations of constructions, via listening tests.

Another approach to this topic is simplified energy-based approach proposed in Odeon or RAVEN software, for example. The separation wall between the 3D modelled rooms is characterised by frequency dependent sound reduction index in one-third octave bands (Fig. 7.2). Simulations are based on particle tracking and its result is an impulse response that also allows auralization (Rindel 2008). In this energy-based method standing waves and other acoustical effects that relate to wavelength won't be detectible but it seems that under certain conditions, this method can be used for the rough estimations (Ronasi 2003).

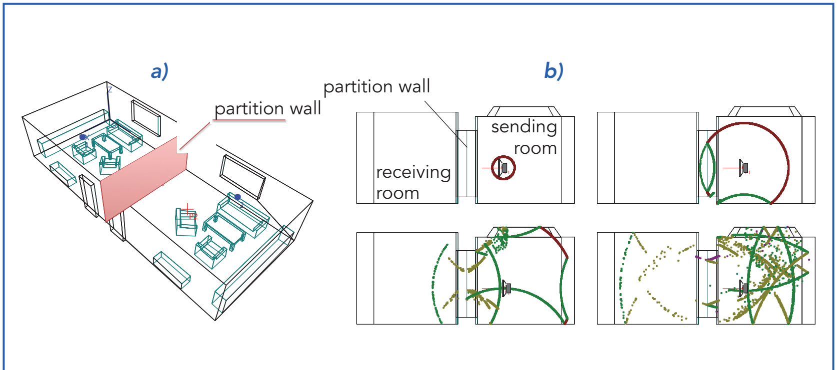

Figure 7.2. *Illustration of the sound transmission calculation by using particle based method in Odeon software a) STSM-TU0901-9967; b) STSM–TU090–6953.*

Ray-based software offers possibility to work with surface sources (partition between two rooms or a floor) that have a frequency spectrum corresponding with the neighbour's sound filtered by the construction. This approach has been used for the assessment of foot-fall noise, including localization of the source (Brunskog et al 2009) and in the framework of proposal for a "living spectrum" in single number rated airborne sound transmission (STSM•TU0901•6953).

7.6. Stimuli and its presentation

Stimuli in listening tests are sound samples used in the listening experiments. In all phases the stimuli can be regarded 'in time domain', as sound pressure as a function of time. When only one isolated feature is examined in the experiment (e.g. test on loudness, pitch, angle of the arriving sound perception), it is called a 1D stimulus. When more than one feature is followed in one experiment, then the stimuli are referred to as multidimensional. In laboratory listening tests, the presentation of the stimuli can be performed by a variety of sound reproduction systems depending on the origin and type of stimuli. The two most common approaches for the presentation are (1) multi-channel loudspeaker systems that reproduce multi-channel recordings or sounds obtained from simulations, while the second approach is (2) headphone presentations. In order to avoid unrealistic reproduction, the influence of the reproduction system itself has to be considered already when preparing the stimuli. Loudspeaker systems allow the subjects to listen in a natural way, with their own ears, but the signals and the distribution of the loudspeakers must be very well balanced and so-called cross-talk cancellation filters that are based on the HRTF need to be used for virtual auditory space synthesis (Akeroyd et al, 2007). Ambisonics represents a feasible spatial sound reproduction technique based on spherical harmonics (Pelzer et al 2011).

When using headphones, front-back confusion can be a problem, due to subtle inaccuracies of the HRTF information related to not properly modelled spatial filtering effect of the pinna. However, the localization in frontal horizontal plane will be affected only minimally. In listening tests for building acoustics, binaural and monaural cues are less crucial than in audiological research. However, to be able to present stimuli in the most realistic way, all recommendations for loudspeaker and headphone presentation systems need to be taken into account.

7.6.1. Visual feedback

Visual stimuli can influence our perception of auditory stimuli. E.g. seeing a speaker in an otherwise empty room already suggests that sounds in that room are originating from that speaker and not from somewhere else. Showing different pictures of nature will influence pleasantness of perceived sound and vice versa. In listening tests, it is therefore important to choose a proper visual surrounding, which should be the same for all listening subjects, and to decide if visual feedback will be given at all. In order to eliminate experimental uncertainty in a listening test, it is important that all subjects undergo the same experimental procedures, considering both auditory and visual conditions.

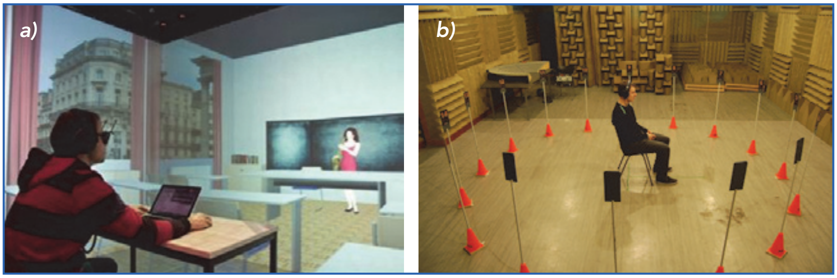

Figure 7.3. *a) Virtual Reality Center at RWTH Aachen University; b) anechoic room at KU Leuven during the headphone experiment on sound localization.*

7.7. Recommendations for listening tests related to sound insulation assessment (proposal of COST TU0901 WG2)

As mentioned earlier in this text, a listening test consists of 4 steps:

(1) recording or synthesizing the original sound signal

(2) modelling or measuring the sound propagating through the medium between the source and the listener's position

(3) definition of the receiver/listener through HRTF

(4) stimuli presentation and data collection methods.

The following text comments on the 4 mentioned steps, summarizes knowledge gained in the framework of WG2 (COST TU0901) and concludes steps on which agreement and consensus between the majority of WG2 members was reached.

7.7.1. Accuracy levels

The quality and reliability of listening tests (for the assessment of sound insulation) is extremely sensitive to (i) sound levels of reproduced stimuli,

(ii) frequency response of the reproduction system (such as headphones) and (iii) the environment in which the listening test is performed. It is not always possible or necessary to fulfil the highest quality of stimuli presentation. Therefore three accuracy levels are defined: (1) Demonstration purposes (Level 1), (2) Survey-type applications (Level 2: level calibration, silent environment), (3) Research purposes (Level 3: level and frequency calibration, sound proofed laboratory)

(1) Demonstrations are in general likely to be made for the representatives of the decision-making government entities, other experts in the related interdisciplinary fields and/or the general public. Level 1, accuracy is required for demonstration purposes. More specifically, it is not necessary to keep the levels of the output sound samples at realistic values, nor is the frequency response compensation of the reproduction system required. Given that such demonstrations will be held in readily available and not necessarily laboratory spaces, it is allowable/advisable to raise the levels of reproduced sound samples to account for the presence of presumably high-level background noise in such spaces. Given the overall listening conditions in such spaces, the frequency response compensation is not of primary concern. To achieve portability, headphone reproduction is preferred over loudspeakers.

(2) Survey-type applications would include e.g. subjective evaluation of sound-insulation properties of new or existing materials or building constructions, in particular in the development process. In that light, level 2 accuracy is demanded, meaning that it is important to maintain realistic levels of output sound samples, even if this means that some of them will not be heard. As a consequence, a noise-free (or at least a low-noise environment, with limited usability) environment is required for performing such surveys. For survey purposes, the frequency response compensation of the reproduction system is optional, but not imperative.

(3) Research applications require level 3 accuracy as important decisions might be taken based on research results. Typical research questions include e.g. the determination of the relationships between loudness of perceived neighbour noise and objective sound insulation measures. This means that it is imperative to apply both level calibration and frequency response compensation. A noise-free laboratory environment is required, with properties described below. Background noise level at each 1/3 octave band must be at least 10 dB lower then sound level of the most silent stimulus, in order to avoid masking effects.

7.7.2. Sound samples description and collection

The core type of stimuli, i.e. source sound samples of interest, is formed around the typical sounds found in daily life, originating from neighbouring dwellings, but also within a dwelling itself, such as speech, music, typical kitchen and bathroom sounds, sounds made by children, party sounds, etc. As sound can originate from outdoors as well, traffic noise is also regarded as an interesting sound to be used in subjective testing. In suburban or rural areas, a significant contribution to the overall sound environment is given by various kinds of outdoor equipment and/or power tools, which makes them worth involving into the investigation as well.

7.7.3. Input files, recording conditions and equipment

Although the reverberation present in the source sound is not critical for sound insulation studies, the general consensus is that source samples should be recorded in anechoic conditions if available. If not, recordings should be made in ordinary rooms in the near field of the source, with the reverberation time in the room not longer than 0.4 seconds. Reverberation in source sound characterized by reverberation time longer than the stated value may be tolerated, but only for presentation/demonstration purposes, while such sound samples should be avoided in the preparation of final test sounds. Objective measures such as equivalent sound pressure level L_{Aeq}, L_{Ceq} or L_{Zeq} should be listed, along with 1/3-octave band spectrum. If possible, loudness parameters should be calculated as well. To describe and/or evaluate the temporal structure of the sounds, statistical parameters such as L_1 and L_{10} should be calculated.

Measuring and recording distance from the source should be set at 1 m, with any deviations clearly stated and the reasons for making them explained. To make the level calibration easier, a 1 kHz calibration tone of a known level should be included into the recording, obtained from a calibration device.

Recording setup should be clearly stated. Mono and stereo recordings are preferred, at the sampling frequency of no less than 44.1 kHz and at least 16-bit resolution. Assuming that the recorded sounds will undergo signal processing, it is recommended to use higher sampling frequencies of 88.2 or 96 kHz, and higher resolutions of 24 or preferably 32 bits, which also provides higher signal-to-noise ratio. After signal processing, the finalized sound samples can be downsampled/converted to lower values of the sampling frequency and/or resolution, if so required by the reproduction method. Only audio formats with no compression must be used, e.g. the .wav format or similar. Audio formats that utilize lossy compression, such as MP3, must be avoided at all costs due to audible compression artefacts. Their use can be tolerated in exceptional cases, for demonstration purposes only. In case of a stereo recording, the recording technique (coincident, near-coincident, or spaced) and specific microphone setup (ORTF, NOS, Blumlein, M/S, etc.) should be noted. Photographs of the recording setup are advantageous.

7.7.4. Output files, reproduction/ playback system

If headphones are used, output sound samples should preferably be binaural in order to avoid in-head localization. Open design headphones are preferred, as closed ones change low-frequency response depending on the "goodness-of-fit" to the listener's head, making the frequency response compensation difficult. On the other hand, closed design provides a certain amount of sound insulation, thereby reducing the background noise perceived by the listener, and making the demands on the listening room and its background noise a bit looser. For demonstration purposes, closed headphone design is a logical choice. (Semi)-open headphones, on the other hand, offer exactly the opposite, in other words, almost no sound insulation from the environment, but easier frequency response compensation, as the fitting to the listener's head is not critical for low-frequency response. These properties make the (semi)-open design ideal for survey and research applications. The drawback of binaural headphone reproduction is the lack of full 3D directional information, specifically, height information, assuming that such kind of reproduction is desired and/or required. The sound samples must be presented on exact relative levels in all accuracy levels (no matter if the files are reproduced at realistic or raised levels). Frequency response compensation (if required) should be easy to implement via 1/3-octave band equalizer, in the stimuli preparation stage. Compensation data will be available for known headphone models, e.g. Sennheiser HD650 or STAX SR-4 Lambda (open), and Beyerdynamic DT770 (closed).

If loudspeakers are used for reproduction of sounds, the output file can consist of 1 up to N channels, where N is the number of loudspeakers. If necessary, reverberation can be added to convolved source recordings in order to simulate realistic receiving room conditions, which is especially suitable for loudspeaker-based reproduction, in which each channel can represent an individual flanking path.

The use of a loudspeaker system, ranging from a single loudspeaker intended for mono reproduction up to an *N*-channel system designed to offer full 3D spatial information and listener envelopment typical for real-life situations can be convenient and suitable for reproduction, in which each channel can represent an individual flanking path. Both Vector-Base Amplitude Panning and Ambisonics are viable choices. Given that it is not necessary to achieve precise localization, but only to give a hint on the general direction the sound is coming from, the size of the system, i.e. the number of loudspeakers can be kept reasonably low ($N \leq 16$ is sufficient in most cases). On the other hand, the increase of the number of loudspeakers stabilizes the sound image, thereby offering the possibility to have more than one listener at a time, provided that the listening room itself is large enough. As a disadvantage of loudspeaker reproduction, each of them inherently introduces additional broadband noise (the amount being dependant on loudspeaker manufacturing quality) into the laboratory space, which then sums up at the listener position, raising the overall background noise profile. The demands on background noise in case of loudspeaker reproduction are even stricter than in case of headphone reproduction.

The use of high-quality components in the entire reproduction chain is imperative, in order to maintain a flat frequency response and keep the background noise level as low as possible. In that sense, built-in sound cards must be avoided; external USB, IEEE1394 or other types of audio interfaces have to be used.

7.7.5. Demands on laboratory for research purposes

For demonstration purposes, the choice of room intended for presentations should be based primarily on the level of background noise. Survey and research applications demand that background noise level is kept as low as possible, desirably at least 10 dB below perceivable limits, if the sound samples are to be played at realistic levels. Higher background noise levels severely disturb both loudspeaker and headphone reproduction based experiment, posing as a limit to the maximum sound insulation that can be presented in such a laboratory. The issue of background noise originating from both outside and within the laboratory must be addressed, the former by ensuring proper sound insulation of the laboratory building itself, and the latter by removing all potential noise sources from the laboratory, other than the ones absolutely necessary for the conduction of specific tests. Equipment such as data projectors, computers, must be placed outside the listening test room. Besides auditory disturbance caused by background noise, no activity that would visually disturb the listeners should be allowed in the laboratory. In that light and having in mind the sensitivity of these tests, i.e. the low-level of the test sounds, it is advisable to perform the test having only one listener at a time, so that multiple listeners would not disturb each other during the test. For loudspeaker-based reproduction, the reverberation in laboratory space has to be kept as low as possible by implementing proper acoustic treatment. If necessary, the reverberation can be added in the stimuli preparation stage in order to simulate normal room conditions, rather than inherently having it in the laboratory space. For headphone reproduction it is also advisable to treat the laboratory acoustically, thereby additionally reducing the level of background noise in the laboratory, thereby additionally reducing the level of background noise in the laboratory. By doing so, the audibility of background noise created by the listening person (caused by movements, breathing…) will also be reduced.

In order to understand the limits asserted by the presence of background noise and to be able to utilize a given space to those limits, it is not sufficient to arbitrarily set the level difference between the reproduced test sound and the present background noise. Both spectral and temporal profiles of background noise in the laboratory have to be recorded. The same basic data as already listed for source files must be given (L_{eq}, 1/3-octave spectrum, statistical parameters). By comparing the spectrum of the test sound with the spectrum of recorded background noise the minimum level of test sound can be determined, assuming that the level of test sound must exceed or at least be equal to the level of background noise in each individual 1/3-octave band. From this data, maximum presentable sound insulation can be determined, having in mind the realistic level of the source and its spectrum, as recorded in the stimuli preparation stage. In general, steady broadband background noise proves to be the easiest to deal with. Time-varying noise and/or the presence of tonal components results in further penalization reflected in required additional increase of the level of test sound.

7.7.6. Subjects (test persons, listeners)

A subject is a person participating on the perception experiment. We distinguish between naïve listener and expert listener. Naïve listener (assessor) is a person who does not have any expertise or knowledge in relation to the test. Expert listener is a person who has knowledge or experience in the investigated field and is competent to give his/her opinion.

The subjects could either represent the entire population, taking into account gender, age and other relevant factors, or be chosen from a pool of young people with, presumably, normal hearing. The question remains whether the hearing of young people is indeed normal and it would be advisable to record the audiogram of each and every listener that takes part in a listening test. In order to perform a meaningful statistical analysis of the results obtained from a test, a minimum number of 30 listeners should take part in such a test.

7.7.7. Psychoacoustic methods (tasks of subjects)

The WG2 of COST TU0901 doesn't prescribe any particular psychoacoustic measuring method, because the choice of a method depends on a type of experiment. However, the most popular methods used in assessment of sound insulation are so far paired comparison test and semantic differential tests and direct ratings in visual analogue scales (VAS).

In pair comparisons, stimuli A and B are compared in pairs. The number of comparisons can be calculated as n(n-1), where n is the number of sounds. Pauses between the sound samples are typically around 1 s. The advantage of paired comparison is, that it gives the listeners the ability to detect small differences in different sounds. The information obtained from such a test is typically of the type "louder/ more silent" or "higher/ lower" without information about the absolute feature of the sounds. In pair comparisons, sound samples are typically between 2-7sec.

The semantic differential gives an assessment of sound by words without comparison with other sounds. Because no direct comparison is intended, pauses between sound samples are recommended to be 10 seconds. The duration of the sounds is typically longer than sound samples for paired comparison tests. If numeric scales are used, e.g. seven- or nine-point scales are recommended (NT ACOU 111). If interval scales are to be used as a basis for specific statistical analysis methods, instruction should be given to test persons to understand and use them as such.

In any tests, it is highly recommended to randomize sound samples so, that no subject would have sounds presented in the same order as the others.

All test persons should get the same explanation about the experiments, preferably written in the form of a short and clear instruction with indication that the test doesn't contain right or wrong answers, but simply goes on subjective perception. Results from tests should be analyzed by statistical analysis (Montgomery 2001; Cohen 1988; Stone&Sidel 1993) in order to indicate relevances and statistical significances.

The tasks that fall within the scope of the listening tests related to subjective evaluation of sound insulation range from demonstration, through survey up to research activities. The research, being the most sensitive part of the three, should focus on determining the relationship between loudness (or annoyance / disturbance / satisfaction) of perceived sound and objective measures that describe the sound insulation properties of building constructions. In that sense, annoyance can also be related to the loudness of the sound in the receiving room, i.e. the one that remains after passing through a wall, a floor or another building construction put under test.

However, a common problem associated with annoyance evaluation is that the laboratory conditions are not at all similar to the usual living conditions, resulting in an out-of-context evaluation not suitable for assessing annoyance. Moreover, the exposure to a sound during a laboratory test is in most cases too short to yield a valid response that would indicate a true degree of annoyance. To overcome these issues, a possible solution is to perform rank tests related to annoyance estimation, rather than insisting on annoyance assessment using an absolute scale.

If complex psychoacoustical percepts are to be addressed, such as annoyance or disturbance, it is very important to define a clear context in which the evaluation should be made. This will help in the interpretation and comparisons of the results obtained in different laboratories. Nevertheless, annoyance or disturbance evaluations (as well as other complex psychoacoustic percepts) derived in laboratory experiments should not be directly compared with annoyance or disturbance ratings derived from socio-acoustical surveys, due to the inherent difference in their elicitation.

In any case, if repeatability of the results is to be achieved for different laboratories, round-robin testing is highly advisable in order to verify or dispute such results and to find additional guidelines for possible improvement.

7.7.8. The importance of listening tests to assess contextual and cultural aspects in sound perception

Psychology plays a large role in the perception and judgement of soundscapes. The sound we produce ourselves in our own apartment (TV, music, cooking, taking shower or talking) have much higher sound levels and often also an objectively much more annoying character (vacuum cleaner or drilling machine) than the sound produced by neighbours. Nevertheless, we very seldom complain about the noise we produce ourselves, while complaints about neighbour noise are quite common.

Irrespective of the objective descriptors, the nature of the activity responsible for the sound produced by neighbours has a large influence on a listener's feeling of annoyance. Finally, the physical and mental activity of the listener himself or herself is a determining factor for his/her assessment of the soundscape, e.g. pleasantness/annoyance of sound. In order to get insight in these factors in combination with the objective parameters, carefully performed listening tests with well controlled variation of relevant parameters represent a valuable tool.

7.8. Research studies performed in the framework of WG2

In the framework of COST TU0901 several studies have been conducted on the subjective assessment of airborne sound insulation in dwellings.

In the research of Horvat et al (2012a) performed during his STSM stay at ITA Aachen and partly at his home institution as well, an examination of required signal-to-noise margin in laboratory subjective evaluation of sound insulation has been performed. The importance of having a noise-free laboratory environment is crucial, if subjective evaluation of sound insulation is to be performed.

Horvat et al (2012b) investigated the suitability of 3D sound reproduction and the influence of background noise on subjective assessment of sound Insulation. Common spatial audio reproduction techniques, namely Ambisonics, Vector-Based Amplitude Panning and Cross-Talk Cancellation were examined, and their potential for use in the listening tests focused on subjective evaluation of sound insulation was evaluated, and the advantages and disadvantaged of each technique were discussed regarding this specific application.

Pedersen et al (2012) have performed a feasibility study on online listening tests on sound insulation of walls. Their listening test was made on the annoyance potential of airborne noise from neighbours heard through walls. 22 assessors from 11 countries rated six simulated walls with four types of neighbour noise online at the assessor's premises using the ISO/TS 15666 annoyance scale. A simple "calibration" procedure based on adjusting a speech sample to natural level for approximate calibration was used.

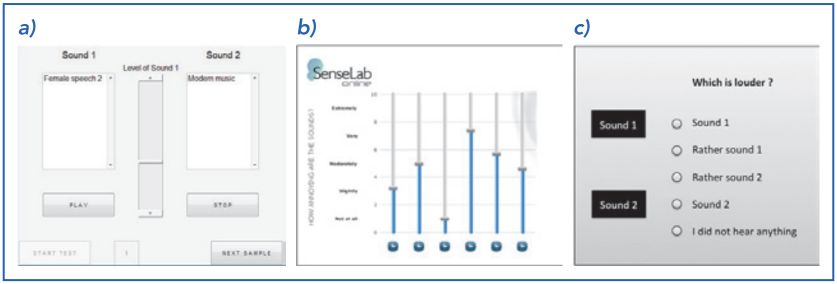

Figure 7.4. *Illustration of the users interface as used in the experiments of a) Horvat et al 2012a; b) Pedersen et al 2012; c) Rychtarikova et al 2013b.*

The preliminary study of Rychtarikova et al (2012a) concerns perceptual comparison of the sound transmitted through two different walls: (1) a light-weight wall and (2) a masonry wall. The two chosen walls had different (laboratory measured) sound insulation spectra *R*, but the same single value rating R_{living} = 51 dB. In spite of their equal R_{living} ratings, significant differences in subjective acoustic insulation performance between the walls are found and therefore it rises the question if the proposed "living noise rating" is the most adequate rating spectrum when considering correlation to perception.

In the study of Ordoñez et al (2013) a façade insulation of 10 different construction types was subjectively evaluated using three psychoacoustic methods: paired comparisons using a two alternative forced choice (2-AFC) paradigm, direct scaling using a visual analogue scale (VAS) of individual stimuli and direct scaling using VAS of five stimuli at once The stimuli used in the evaluations were obtained by filtering recordings of traffic noise with the frequency response of sound insulation measurements. The measurements were performed in typical Italian buildings in accordance with the ISO 140-5 standard. The objectives were to compare subjective sound insulation quality obtained with the three psychoacoustic methods, and to investigate the correlation between the subjective assessments and objective ratings of different construction types.

Hongisto et al (2013a) show preliminary results of a laboratory experiment on disturbance caused by airborne living sounds heard through walls. The aim was to determine the correlation between the most typical single-number quantities (SNQ) of airborne sound reduction index and perceived disturbance in domestic context. Special care was taken to design the experiment so that different living sounds, realistic sound levels and a wide spread of typical party walls were used. The focus was within 50 and 5000 Hz. 26 subjects participated in the experiment. Each participant evaluated the disturbance of 54 sounds while imagining that they were at home relaxing and reading a magazine. Based on this study, it seems that other well-known SNQs, like R_{speech} and R_w, can also be primarily considered because they predict disturbance slightly better than R_{living}.

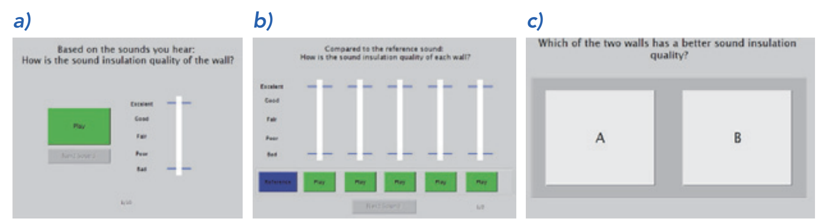

Figure 7.5. *The users interface in the experiment of Ordoñez et al (2013). The user interfaces: a) direct scaling of single stimuli; b) direct scaling of five stimuli; c) paired comparison.*

In the research performed by Hongisto et al (2013b) the main research questions are related to "How standardized single-number ratings of airborne sound insulation predict subjective perception of various living sounds"? In this study, fifty-nine subjects participated in the experiment. Each participant evaluated the disturbance of 54 sounds while imagining that they were at home relaxing and reading a magazine. Six spectrally different living sound types were examined. It seems that the disturbance is predicted relatively well by SNQs focusing on the frequency band 100-3150 Hz.

Thorsson (2013) conducted laboratory listening tests on footfall sounds. Based on the literature study a listening test methodology has been devised that one can use with measured data from field situations. The recorded acceleration signals were reproduced using ceiling-mounted loudspeakers and subwoofers. The reproduction system was designed to reproduce signals down to 16 Hz and the reproduction level was measured to be equal to footsteps on the real floor. The listening test was done using pairwise comparisons between one sound with fixed level and one sound where the subject could vary the reproduction level. Two questions were used in the tests: 1) adjust the sounds to equal annoyance, and 2) adjust the sounds to equal loudness. Different objective measures for evaluating the footstep sounds were tried using the residual between the mean subjective score and the value of the objective measure as error marker. The minimum residual sum of all listening test comparisons was the average A-weighted maximum level.

The article of Rychtarikova et al (2013) presents the effect of temporal and spectral features of the presented stimuli on loudness perception. In their study, 15 different stimuli with duration of 5 seconds were presented to subjects via headphones in three ways: (1) original daily life signals, auralized as they would sound as after being transmitted through the wall between neighbouring apartments, (2) the time inverted version of the signals in (1) and (3) noise stimuli filtered such that they had the same spectrum as the signals in (1), but without the amplitude modulations (i.e. resulting in a stationary signal). The goal of comparing (3) with (1) was to assess the influence of amplitude modulations on the loudness perception of transmitted sounds.

Although not in the framework of COST TU0901 an interesting overview about the procedures in listening tests in science and industrial praxis has been published in a framework of DEGA, edited by Hellbrück et al (2008).

7.9. Conclusion

The perception of sound is a complex process, since it involves not only objective but also subjective factors. In order to gain insight in this process, it is not only important to accurately determine room acoustical, building acoustical and psychoacoustic parameters, but also to evaluate their relevance and appropriateness for different acoustical scenarios, and, where necessary, to conceive new measures and criteria for judgement of acoustical scenes. Provided they are carefully designed, listening tests performed *in situ* and in laboratory conditions offer an indispensable tool in acoustical research and development of acoustical tools, since they compile all relevant aspects mentioned above, thus strengthening the validity of conclusions and the reliability of resulting acoustic qualifiers.

Development and advancing research in high quality auralization (measurement and simulation based) remains one of the most important research topics for future. Simulations of not only airborne transmission but also flanking and impact noise transmission should be addressed in new research proposals.

More investigation should also be done, comparing different psychoacoustic methods that can be used for validation of a variety of acoustic parameters. Here collaboration with psychologists and audiologist is essential.

A round robin test on listening tests would be a great opportunity to test the uncertainties related to different laboratories and reproduction systems and their impact on listening test results.

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8

Correlating Objective and Subjective Sound Insulation

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CHAPTER 8 Correlating Objective and Subjective Sound Insulation

8.1. Introduction

Measures against noise in dwellings should lead to protection of residents from noise coming from outdoors, neighbours, plumbing and other building equipment, e.g. elevators. Normal and reasonable living activities in its wide range like listening to music, watching TV, children playing, however, should be also possible without to limit the neighbour's living comfort with these activities.

During the last decades the demand on living standards has increased and building techniques have partly changed. There is strong evidence that the currently applied requirements and descriptors do not consider the residents' experience of the building acoustical comfort sufficiently c.f. (Mathys, 1993; Rindel, 1999, 2003; Lang, 2006; Rasmussen, 2010; Rasmussen et al, 2010). To be able to develop applicable prediction models and standards, appropriate descriptors and requirement systems which are strongly related to human perception are needed.

In the broadest sense even the traditional reference curves according to ISO 717-1 and 717-2 (2013) and preceding versions back to ISO Recommendation R 717 (1968) have a kind of perceptual implication, eg. the characteristic was an approximation of a wall which was proven regarding sufficient sound insulation properties with the typical living standards in those years. An elaborate analysis and documentation regarding the diversity and the development of the applied descriptors as well as the different regulation systems over the last decades in Europe can be found in (Rasmussen et al, 2005, 2010; Rasmussen, 2010, 2012).

Rating systems of future performance specifications of buildings should be in close relation to the contemporary living standards as pointed out by Scholl et al (2011). This means the single-number quantities have to correspond closely to the human perception of noise which is a quite complex challenge because there is still insufficient knowledge about correlation between objective and subjective sound insulation issues, especially in relation to the low frequencies (Waye, 2004, 2006; Leventhall, 2004). Thus, the relation of building acoustic descriptors and human perception has to be investigated more closely to meet the contemporary living standard aspects. So far, however, there is no appropriate assessment tool established in general, which would provide proven reliable psychophysical and sociological data in close relations to building acoustics conditions.

Beyond that it is necessary to develop single number quantities with high degree of correlation to the subjective rating of sound insulation, independent of the type of the materials of the building elements and building concepts.

8.2. Subjective assessment of sound insulation quality in buildings

To conduct surveys in order to get a better idea of the relation between noise annoyance and sound insulation properties of the buildings is not really new. There were many approaches over the last decades to get empirical data - subjective (degree of annoyance) and objective ones (measured sound insulation values) regarding sound insulation properties of buildings in detail cf. e.g. (Bruckmayer et al, 1974; Bradley, 1982; Rindel, 1999). A brief overview regarding these kinds of activities in Poland since the early 1980s is given by Izewska (2010). Very recently a study has been conducted in Finland cf. (Hongisto et al, 2013).

During the early seventies of the last century for example a study has been carried out in Austria to find the basic aspects to be able to establish reasonable new sound insulation requirements (Bruckmayer et al, 1974). With an extensive survey with more than 2000 analysable questionnaires as well as with an extensive number of sound insulation measurements in the buildings of the respondents subjective and objective data were gathered. Investigated were not only airborne and impact sound insulation between dwellings, but also between dwellings and staircases as well as the sound insulation properties of facades and windows. Like in the harmonized Working Group 2 questionnaire, plumbing noise and noise of domestic equipment had been taken into account, too. In addition to the rating scale approach open questions were asked and spontaneous comments of the respondents were welcome in the applied questionnaire. Analysing such combined datasets is rather demanding, but it gave valuable complementary informative clues interpreting the statistical data.

Based on this study the Austrian requirements were derived and are still largely applied in the same way. Since 2012 a classification system is available (ÖNORM B 8115-5) with the opportunity to apply higher sound insulation requirements also taking the frequency range below 100 Hz into account.

A similar study was conducted in Canada by Bradley (1982). This very thoroughly prepared study regarding the design of the questionnaire and organising the measurement as well as the analysis of the data was meant as a pilot study to get basic insights for preparing a follow up study in a large scale. This study is also very interesting because the questionnaire applied had been analysed regarding the basic test statistical criteria.

One of the objectives of the study was to compare the sound insulation descriptors applied in those days regarding their accurateness predicting the degree of annoyance as an reaction of the residents' caused by their neighbours.

Due to the character of a pilot study it was the aim to keep the number of confusing influences as low as possible. Thus, only the airborne sound insulation of partitions between row houses and also between dwellings in apartment buildings (but in a smaller number) was considered. It was their idea that the sound insulation situation of row houses is simpler to interpret in comparison of the much more complex circumstances in apartment buildings. The subjective responses were gathered by trained interviewers in each of the dwellings. Results were mainly obtained from pairs of adjacent row houses as mentioned (84%) and from adjacent flats in apartment buildings. In the analysis 98 respondents were included, together with measurements of the background noise levels in the 98 homes and the sound insulation properties of the 49 common walls.

The findings of both studies together (Bruckmayer et al, 1974; Bradley, 1982) provide valuable ideas for the interpretation of the investigations done with the harmonized questionnaire so far as well as efforts of further improvements which might be considered in the future.

8.3. Basic aspects regarding questionnaires and listening tests

8.3.1. Distinction between laboratory tests and field studies

Field study and laboratory experiments are often discussed as kind of competitive methods, but in fact the aim of both methods is quite different cf. (Zeidler, 2000; Bortz et al 2002; Myers et al, 2003; Montgomery, 2009). In the discussions the (quantitative) field study is meant to be more valid in comparison to laboratory experiments because it takes place under real life conditions, but actually both methods have to be seen as complementary on the same level of relevance. In fact, the choice which method has to be applied depends on the aim of a study. With the laboratory experiments one gets the strongest tool in natural science because if all the rules and standards are met, e.g. correctly randomised samples controlled conditions etc. It allows drawing causal conclusions and influences as well as possible interaction of the variables taken into account can accordingly be distinguished. Such thoroughly designed and conducted experiments are an indispensable tool for the development and confirmation of prediction models and theories. In comparison, field experiments have a high level of external validity, models and theories can be checked if relevant effects can be seen as predicted quite close to real life conditions, which is necessary to be able to generalise the findings. Questionnaires are important tools to investigate many aspects in social and behavioural science in real life environments.

Thus, in case of the investigations and research efforts regarding sound insulation properties laboratory listening tests have to be carried out to find details concerning relevant perception aspects to be able to propose the most appropriate sound insulation descriptors. Questionnaires have to be applied in the field to find the appropriate sound insulation requirements to ensure most satisfactory living conditions from the viewpoint of the noise protection.

8.3.2. Basic quality criteria and standards

Basic scientific quality criteria and standards have a significant impact on the results of tests and conducted surveys. Thus, it is important to mention them in this chapter in particular, because these aspects will contribute and support interpreting the results of the investigation carried out with the developed draft questionnaire so far.

Psychological and sociological tests (listening tests are in their basic principles psychological tests in the field of perceptual psychology) as well as questionnaires of any kind have to be considered as measurement instruments. This aspect is very often neglected if behavioural or perception data is investigated in other fields of research than social and behavioural science. All the criteria and requirements which other measurement appliances in the field of physics for example have to meet to measure certain physical properties, have to be applied with psychological test batteries and questionnaires as well otherwise the obtained results are not usable for the purpose of serious research because it is simply not known what these datasets really characterize. Thus, three basic criteria have to be analysed during the process of developing such subjective assessment tools. These most basic criteria are objectivity, reliability and validity.

If the results of a questionnaire or psychological test of any kind are unbiased by a possible influence of the experimenter or interviewer for example the procedure can be considered as objective quite sufficiently. Regarding questionnaires an interviewer or how the form is received by the respondent can cause a rather significant influence on the response behaviour of the subjects. It can be expected that with trained interviewers, for example, this important aspect of uncertainty could be minimized (Fowler et al, 1990).

Two other most important aspects of precision are reliability and validity. Reliability refers to the reproducibility of a measurement (Rost, 1996; Fowler, 2009). Obtaining the same result after multiple tests means a test or a questionnaire is reliable but without the proof that the test or the questionnaire is measuring what is intended to be measured.

The type of test or questionnaire being administered must measure what it intends to measure (Rost, 1996; Fowler, 2009). The term validity in this context characterizes the extent to which a test measures what it claims to measure. It is vital for a test and questionnaire to be valid in order for the results to be accurately applied and interpreted. Validity is not determined by a single statistic, but by a body of research that demonstrates the relationship between the test or questionnaire and the response (attitude, reaction or other kind of behaviour) it is intended to measure. Thus, just to ask for a response is not enough to be sure that one gets what is intended to get. This fact has to be taken very seriously regarding all kinds of tests and surveys applied.

8.4. Application of the COST TU0901 questionnaire

After the discussion of the proposed COST TU0901 Working Group 2 questionnaire within the WG a first draft was presented firstly in English by Christian Simmons (Simmons et al, 2010 and Simmons et al, 2011a).

The applicability as well as the quality of the questionnaire is shown below by two already published studies as examples conducted in Sweden (Simmons et al, 2011b) and in Italy (Di Bella et al, 2012), where a draft of the questionnaire had been applied. There are more investigations which are currently conducted, e.g. Portugal, Serbia and Slovakia, but they are at an early stage or at the stage of analysing the data.

8.4.1. Example 1 – Swedish Study

This questionnaire which has been proposed was applied in a quite extensive Swedish study where the survey was conducted in 10 apartment buildings (Simmons et al, 2011b). Half of the buildings were with concrete floors and partitions to be compared with the other five which were built in light weight mode of construction with timber joist floors and walls. In these buildings airborne as well as impact sound insulation tested according to ISO 140 and ISO 717 had been carried out, also with a focus on the extended frequency range down to 50 Hz. In the concrete buildings calculations according to EN 12354-1 and 2 had been carried out to get the objective sound insulation data.

The questionnaires were sent by mail or by direct distribution to the selected buildings, where all residents received an introduction letter with the explanation of the purpose of the study and a questionnaire. To collect the answered forms different approaches were chosen. One approach was that the residents received a response envelope with the return address and a stamp attached, and the other approach was that a temporary post-box was positioned in the ground floor close to the entrance of the buildings where the respondents could put their completed questionnaires.

The response rate was quite good compared to the usual rate which can be expected by this kind of surveys. In the concrete houses, the response rate was between 60% and even 90%. In the wooden houses, the response rate was more than 70% in 3 of the buildings and around 50% and 35% in two of them. In total, there were analysable forms from 305 respondents of the concrete buildings and 149 respondents of the wooden buildings.

According to the reported results the correlation was rather weak regarding the airborne sound insulation aspect but stronger if the impact sound insulation was taken into account. One of the findings obtained by the analysis of the gathered responses was that residents in the buildings with concrete floors and partitions were slightly disturbed by airborne noise from the neighbours and somewhat more disturbed by impact noise (cf. Table 8.1). Noise from technical equipment and traffic were more pronounced, if structure-borne noise from elevators and toilet flushes are considered for example. Overall the ratings by the residents can be considered satisfying or good.

Table 8.1. Degree of disturbance in the concrete houses investigated

concrete houses degree of disturbance	airborne sound insulation	impact sound insulation
very disturbed	5%	10%
disturbed or very disturbed	10%	15%
somewhat disturbed, disturbed or very disturbed	20%	20%

Residents of the wooden buildings taken into account in the study were slightly disturbed by airborne noise from the neighbours and technical equipment, but impact noise was indicated to cause considerable annoyance in all of the timber frame buildings (cf. Table 8.2).

Table 8.2. Degree of disturbance in wooden houses investigated

wooden houses degree of disturbance	airborne sound insulation	impact sound insulation
very disturbed	5-10%	25-30%
disturbed or very disturbed	10-12%	50-55%
somewhat disturbed, disturbed or very disturbed	20%	60%

The objective sound insulation measurements indicated satisfying performance but this was not confirmed by the ratings of the residents, which probably can also be explained with problems if the currently applied sound insulation descriptor is used to characterize impact sound insulation properties of light weight buildings in particular. One evidence which supports this assumption is that if the frequency range is extended down to 20 Hz, the correlation coefficient increases up to r = .85 (reported by Simmons at WG2 meeting Bucharest 26 and 27 September 2013).

According to the authors, the results from these surveys were amended by data from previous studies (Hagberg, 2010; Bodlund, 1985) to increase the appropriateness of the entire dataset for explorative analysis regarding correlations between subjective ratings of the residents and objective measurement results. A reasonable correlation was found between ratings and the calculated and/or the measured normalized impact sound pressure level $L'_{n,w}$ combined with the adaptation term $C_{I,50\text{-}2500}$ ($L'_{n,w} + C_{I,50\text{-}2500}$) which takes the frequency range down to 50 Hz into account.

The correlation between airborne sound insulation, also including the frequency range below 100 Hz, however, was still rather low even with the extended data.

8.4.2. Example 2 – Italian Study

A similar study but in a smaller scale has been conducted in Italy (Di Bella et al, 2012). A draft version of the harmonized WG 2 questionnaire was applied in 9 buildings where measurements of the airborne and impact sound insulation had been carried out, too.

The correlations of both for airborne and impact sound insulation have been considerably weak. The subjective responses were evenly distributed to the different sound insulation values measured, also adding spectrum adaptation terms to include the low frequency range. The authors of the study reported that in particular for the impact sound insulation many positive values have been found although extremely poor levels of performance were objectively given.

8.5. Discussion

To apply questionnaires to get information about living comfort expressed by the residents and sound insulation properties of buildings has been a common approach over the last decades. The obtained correlations were considerably poor and it was only possible to draw rather vague conclusions. If sophisticated sound insulation classification systems have to be derived as basis for new, more appropriate requirements, much more accurate surveys are necessary to get meaningful correlations regarding sound insulation and subjective responses. Thus, in this respect, it was one of the ambitious objectives of this COST action, to develop a harmonized and effective draft questionnaire.

Never practically applied before, the Swedish as well as the Italian study have to be seen as pilot studies to check the practical applicability of the questionnaire as well as the ability to discriminate building acoustics comfort levels sufficiently.

In the Swedish study the correlation was rather weak regarding the airborne sound insulation aspect but a stronger relation has been shown if the impact sound insulation was taken into account. The response data showed lower annoyance levels than in the light weight buildings, which was also because the concrete buildings were designed with higher sound insulation performance than required by the Swedish building regulations (cf. Simmons et al, 2011b). The higher correlation of the impact sound insulation was mainly due to the larger variation of impact sound insulation performance of the light weight floors in the light weight buildings.

If airborne sound insulation is considered, then it can be seen that the sound insulation level was quite on a high level and also the variation was obviously not large at all which means that the sample, particularly the concrete building sample, has to be regarded as a cluster-sample which in principle shows only low correlation coefficients. Beyond the physical point of view many other influence aspects which are mainly of sociological and psychological origins have to be expected as well. In the Swedish study some other discrepancies regarding subjective response data and sound insulation results were checked by inspections on some of the sites which led to very interesting additional information about the specific situations. Here only a few remarkable examples are mentioned, just to adumbrate the complex interactions which have to be expected regarding living situation, noise exposure, noise annoyance, objective data and subjective ratings by the residents.

It has been reported in one situation where once a week, garbage bins are emptied with a vacuum blower truck, which causes high noise levels during day time, the ratings by the residents were unexpected moderate. In an experimental study (Cederlöf et al, 1963) it has been shown that noise ratings of vehicles depend considerably on the purpose of the vehicle. If there is a positive attribution like to be on duty for a delivery or emergency tour the rating is considerably lower than that if the attribution is less positive, for example, if a teenager is passing-by with his or her motor scooter in comparison to a postman for example. The same explanation is probably appropriate regarding the reported situation that an ambulance helicopter is clearly heard but is not perceived as disturbing according to some residents' opinions. It may be heard also when preparing for take-off from the roof of the nearby hospital, but is not considered as disturbing. In contrary it is regarded as disturbing if heavy vehicles passing by the houses on the local street in spite they are not supposed to drive on this street.

Similar experiences have been reported in the Austrian study (Bruckmayer et al, 1974) where with noise events caused by necessary living activities the ratings have been much more moderate than if they were not attributed as necessary. If the residents are asked how annoyed they are because of their neighbour's noises, it has to be expected that the sound insulation of the wall, floor or ceiling is not the only aspect which determines the rating. In the Canadian Study (Bradley, 1982) it was reported that many subjects, although clearly exposed to noise, wouldn't say or indicate that they were annoyed because of their relationship with the neighbours in question. The authors of the Italian study (Di Bella et al, 2012) gave a similar explanation regarding their response data.

8.6. Conclusions

The big step forward and achievement of the COST TU0901 approach in comparison to the many previous applied ones is that now a harmonized questionnaire will be available as basis for further research. The questionnaire has been translated into many different languages and if once sufficiently evaluated and validated future studies will be comparable and will give much more important and reliable information for further research and development efforts (e.g. about cultural influences on sound insulation needs in more detail) than it has been possible so far.

Another implicit aim was to try to keep the questionnaire as short as possible, which is a different approach in regard to both "historical" examples mentioned above, where beyond sound insulation and noise annoyance questions extensive social and psychological aspects were taken into account as well.

To keep the questionnaire very short has an influence on its properties to measure what is intended to measure (concerns validity and reliability). Questionnaires or tests with composite scales (more different questions are asked regarding one aspect) are in principle more accurate than if only single response items are applied. This is also of relevance if noise annoyance related questionnaires are taken into account (Bradley, 1982).

The studies done so far give an interesting insight regarding the applicability of the questionnaire as well as first ideas about the quality to discriminate certain comfort levels, but they have to be seen as a first glance concerning the accuracy criteria of the questionnaire. More studies are necessary to be able to estimate the exact quality of the questionnaire more accurately. Studies are also mandatory regarding the validation of the statistical properties of the translated questionnaires to ensure that they all measure largely the same aspects.

Beyond the physical point of view many other influence aspects, which are mainly of sociological and psychological origins have to be expected cf. (Bruckmayer, 1974; Bradley, 1982; Cederlöf, 1963). Listening tests and more detailed interviews with residents should be made to find out what reasons there might be behind large discrepancies concerning subjective responses and objective sound insulation properties of the buildings.

In this respect it would be beneficial to establish a kind of "standardized presentation" of the questionnaire, because it matters how the response data is gathered beyond the design of the questionnaire itself. Trained interviewer will contribute positively in getting more reliable response data. Particular situations can be taken into account by asking (standardized) open questions and noting spontaneously uttered comments by the residents. Thus, an appropriate guideline in regard to create a specific uniform training concept (also in regard with cultural aspects) for interviewers should be developed.

For further investigations the suggestion of the authors of the Swedish study (Simmons et al, 2011b) should be taken into consideration that measurements in buildings included in a survey should be extensive, to allow for determination not only of the average insulation but also for the variation inside the building. It remains to study whether another, from the perceptual point of view, more sophisticated characteristic values than the average sound insulation would improve the correlation to the subjective ratings, e.g. using a lower fraction of insulation within a series of measurements rather than their averages.

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9

Monitoring & Testing Sound Insulation Performance in New Homes in Europe

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CHAPTER 9 Monitoring & Testing Sound Insulation Performance in New Homes in Europe

9.1. Introduction

This chapter discusses the role of monitoring and checking the performance of sound insulation in new homes across different countries. The content of this chapter and information on each country was provided by members of COST ACTION TU0901 during the course of the project. The information presented here was updated and finalised in October 2013. As such in future years some countries may change their approach to testing and monitoring performance. This information provides a useful "snapshot" in time of current practice and procedures.

A total of 29 countries participated within this review and countries were asked to respond to a range of questions and queries relating to:

- Requirements for sound insulation testing on new attached housing
- Site monitoring, inspection and possible use of construction checklists
- Implementation of checklists or third party central database of on-site (field) testing undertaken
- Tolerances and uncertainty permitted in reporting and assessing single weighted field performance results.

9.2. Requirements for Sound Insulation Testing in Europe

Table 9.1 provides the results of the survey relating to requirements for sound insulation testing on separating walls and floors in new attached housing. It can be seen that 7 of the 29 countries have mandatory testing through national requirements and 5 countries have local or regional requirements for sound insulation testing. The UK appears under both categories due to the diverse sound insulation requirements and building regulations found for Scotland, England, Wales and N. Ireland.

Only the UK has third party centralised databases of recording sound insulation testing which are operated by Robust Details Ltd and the Association of Noise Consultants.

24 of the 29 countries have sound insulation testing undertaken where the client (e.g. developer) may request such testing to prove or check that compliance with building regulations has been met. But this will depend on the client's interest for such information and willingness to fund such tests.

10 of the 29 countries have systems or processes whereby for additional eco-ratings or sustainability ratings additional sound insulation tests can be undertaken. This may often allow the housebuilder, contractor or developer to achieve a certain sustainability rating or credits or points towards that rating.

All 29 countries have had experience of utilising sound insulation testing when investigating complaints which illustrates the accepted appeal of a sound insulation test process as a mechanism to investigate issues and determine causes.

9.3. Permitted Tolerances on Sound Insulation Testing

A sound insulation test if undertaken in the field in real housing most often uses the frequency range 100Hz to 3150Hz. This can vary in different countries for example in Sweden the range is extended to lower frequencies such as 50Hz. The corresponding weighted result for airborne or impact sound is presented as a single figure, e.g. R'_{w} = 53 dB or $L'_{nT,w}$ = 53 dB.

To express a sound insulation test result as a singular value would involve the calculation of over 100 recorded data values involving reverberation time, sound pressure level, background noise etc.. This calculation process may involve 'rounding' to one decimal place and also for some acoustic criteria inclusions of the measurement of the room volume and separating test surface area (for a wall or floor).

Given the number of measured data values utilised within a singular sound insulation test result it may be possible to have a value of uncertainty or tolerance which is permitted when comparing the test result with the regulatory requirements.

In some countries the regulatory requirement for airborne and/or impact sound transmission is set as an absolute minimum with no averages or variations permitted. In some countries a minimum value for airborne (maximum for impact) is set whereby an additional tolerance for uncertainty is allowed and this may vary from 1 dB to 3 dB.

Table 9.1. Comparison of sound insulation testing processes on new homes via regulations or client requests

COUNTRY	Is it mandatory to carry out sound insulation testing in your country (Nationally)?	Is it a requirement to carry out sound insulation testing in some local or regional areas?	Are national or regional sound insulation tests recorded in a central organisation (3rd Party) database?	Is sound insulation testing carried out as instructed by Clients on new buildings? (e.g. Developer, housing association)	Are additional sound insulation tests undertaken sometimes for specialist RATING? (e.g. for an ECO, Sustainability rating)	Are sound insulation tests carried out sometimes when investigating complaints for sound insulation?
AT		X			X	X
B				X	X	X
CH				X		X
CZ	X			X		X
DE				X	X	X
DK				X		X
ES		X		X		X
EST				X		X
FIN				X		X
FR	X			X		X
GR				X		X
HR				X		X
HU				X		X
IS				X	X	X
IT		X		X		X
LT	X					X
MK					X	X
MT				X		X
NL				X	X	X
NO				X		X
PL				X		X
PT	X				X	X
RO				X		X
SE		X		X	X	X
SI	X					X
SK	X			X	X	X
SR				X		X
TR				X		X
UK	X	X	X	X	X	X
	7	5	1	24	10	29

The following table 9.2 shows the permitted tolerance or uncertainty levels which may be utilised in each country which responded to this survey for:

- Airborne sound insulation for separating walls
- Airborne sound insulation for separating floors
- Impact sound transmission for separating floors

Summarising the results of this survey it can be seen that:

- 21 of the 28 countries do not permit any tolerance or level of uncertainty to the reported values from on-site testing
- Denmark permits tolerance of 1 dB
- Austria, Belgium and Sweden permit up to 2 dB
- Spain, France and Portugal can allow up to 3 dB tolerance

9.4. Onsite Inspection and Monitoring Workmanship for Sound Insulation

On-site inspection and monitoring for sound insulation varies for different countries. Whilst sound insulation may form part of a country's building regulations the mechanism by which inspection is undertaken or compliance is checked on the construction process varies significantly in different countries.

The guidance for the construction of a wall or floor system may be set within building standards or guidance, known as a 'prescriptive approach'. Alternatively the regulation may be 'performance based' only and no specific technical guidance is given.

In some countries the sound insulation regulation and guidance may involve both 'prescriptive and performance' based, whereby construction technical standard drawings are provided and performance testing is also undertaken.

Inspections may be undertaken as part of a local authority building control or building inspector portfolio of work. However, in some countries additional or alternative inspection processes are also undertaken.

Table 9.3 illustrates where additional support is provided for monitoring and checking workmanship. This can be summarised as:

- Three countries (Belgium, Spain and UK) currently have specific checklists available for site workmanship to be monitored for particular wall and floor constructions

Table 9.2. Comparison of sound insulation testing processes on new homes via regulations or client requests

COUNTRY	No tolerance or uncertainty is currently specified and the minimum regulatory value must be met (o)	Tolerance of 1 dB with respect to the requirement	Tolerance of 2 dB with respect to the requirement	Tolerance of 3 dB with respect to the requirement
AT			X	
B			X	
CH	X			
CZ	X			
DE	X			
DK		X		
ES				X
EST	X			
FIN	X			
FR				X
HR	X			
HU	X			
IS	X			
IT	X			
LT	X			
MK	X			
MT	X			
NL	X			
NO	X			
PL	X			
PT				X
RO	X			
SE			X	
SI	X			
SK	X			
SR	X			
TR	X			
UK	X			
	21	1	3	3

Table 9.3. Use of checklists, specialist acoustic inspections and monitoring

COUNTRY	Are building acoustic site checklists provided for common wall or floor constructions?	For rating requirements are building acoustic experts required to visit construction sites to inspect and monitor workmanship?	Do clients sometimes request building acoustic experts to inspect and monitor workmanship?
AT			
B	X		X
CH			X
CZ			X
DE		X	X
DK			X
ES	X		X
EST			X
FIN			X
FR			X
HR			
HU			X
IS			X
IT			X
LT			
MK			X
MT			X
NL			X
NO			X
PL			X
PT			X
RO			X
SE			X
SI			X
SK			X
SR			X
TR			X
UK	X	X	X
	3	2	25

- In the case of Germany and the UK building acoustic experts may be required to visit and inspect constructions as part of a third party process (e.g. for acoustic ratings)
- 25 of the 28 countries may sometimes request acoustic experts to inspect and monitor as part of a Client's request.

In the latter case this would depend on the client and whether they wished to ask or fund such additional inspections and thus not all homes or construction sites would be able to have such inspections.

In the UK through the robust details (www.robustdetails.com) scheme they provide a comprehensive portfolio of monitoring and support which the developer can register to use, involving:

- guidance constructions and detailed technical specifications,
- checklists for site managers,
- random site inspections undertaken by robust detail inspectors for feedback to site managers,
- and, sample sound testing and feedback to site managers.

9.5. Case Study - UK

The effectiveness of site monitoring and checklists has been on going in the UK since 2004 following the introduction of robust details in England. Scotland also adopted the robust details scheme in 2011 although for different regulatory performance requirements than England.

Since its inception over 8,000 subscribers have utilised the design RD Handbook which gives detailed 'prescriptive' technical specifications. There are over 50 robust detail separating wall and floor designs providing over 200 wall and floor combinations for use in apartments and flats.

During the last 9 years over 650,000 new homes have been built using the designs and the compliance levels for sound insulation performance have risen from 50% pre-robust details to 99% with robust details. Noise complaints reduced by a factor of four in new build homes since their introduction.

The scheme involves over 25 robust detail inspectors spread across the country and are subcontracted from acoustic consultancies to undertake random site inspection and monitoring of the construction process.

One of the specific attributes which has made the scheme so successful is that it was designed by industry with guidance and support from the government, acoustic research experts, local authorities and warranty providers. The multi-combination of stakeholders involved allowed a significant amount of knowledge transfer to occur in a short space of time. The site inspections by robust detail inspectors have provided a close-up knowledge exchange and transfer of how to improve workmanship and guide site operatives and managers whilst also providing an important feedback loop of future amendments to specifications, designs and updating checklists. All sound insulation site test data is gathered into databases which has led to national monitoring of construction types, workmanship and performance.

9.6. Conclusion

This chapter has provided a useful insight to the variation of inspection and monitoring which occurs across European countries. Whilst many countries may use additional acoustic guidance, expertise and sample testing via client requests few countries provide a regulatory or 'prescriptive and performance' approach to sound insulation.

Uncertainty and tolerance permitted to singular weighted sound insulation values is very limited. The use of helpful checklists for site operatives and site managers is limited and could be utilised more as is only adopted in Belgium, Spain and the UK.

A unique aspect which has driven up standards of workmanship within the UK was the introduction of compulsory sound insulation testing, checklists, technical guidance and site inspection by acoustic experts.

COST
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Building acoustics throughout Europe
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10

Common Errors and Good Practice in Design and Workmanship

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CHAPTER 10 Common Errors and Good Practice in Design and Workmanship

10.1. Introduction

A great variety of design and construction techniques have been described from around the European Union and beyond. COST action TU0901 has provided a unique opportunity to exchange practical experience of the design, construction and in-situ performance of these diverse construction types and techniques.

This chapter highlights good practice in design and implementation to assist in learning from other's experience to improve future housing standards. The absence of good practice can lead to workmanship errors. These are also highlighted to help those involved to learn from site experiences of others, and to avoid duplicating mistakes. In this way the collective expertise can benefit all, helping designers and builders to make the most of the materials at their disposal to deliver the best sound insulation achievable considering practical and economic constraints.

Although separated for clarity, it should also be noted that good practice design and workmanship should be considered holistically, with each informing the development of the other. Good designs are often those which are easier and more logical to implement, thereby being less prone to workmanship variability. Good workmanship involves thought and care, with an appreciation of key aspects such as flanking transmission. Thoughtful construction can then feed back into more robust design solutions based on the experience gained on site. Building codes which encourage this symbiosis between effective design and good construction practice has been shown to deliver sound insulation improvements to citizens.

10.2. Design: common errors and good practice

This section shows good practice design to achieve acoustic comfort in housing or to meet the legal requirements.

First, dwelling layout is discussed as an initial step to achieve acoustic quality, secondly an overview of different types of separating walls and floors is given, as well as recommendations to minimize flanking transmission.

Although this COST action is integrated by 29 different countries, where regulations, techniques and types of constructions differ widely, some of the recommendations and errors can be considered common and extensive. It is important to note that some of the advice must be considered in the context of the level of the field sound insulation that has to be reached.

Finally, best practice design does not ensure a good acoustic performance, if workmanship is not adequate (see sections 10.3 and 10.4).

10.2.1. Good layout as the first step for good sound insulation

The first step towards achieving good sound insulation in housing is a good layout. When possible, placing noisy areas, such as bathrooms, kitchens or mechanical rooms adjacent to each other and far from quiet areas, such as bedrooms, is the best way to maximise comfort. In this sense, vestibules, corridors and halls can be used as buffer spaces between noisy areas and quiet areas. This also favours the construction of service pipes, ducts and passive fire protection.

The first draft of schematic plans made by architects can have a significant impact on the acoustic quality as important decisions are made about rooms in adjacent dwellings. Having a good sound insulation layout is sometimes complicated, such as in alterations of existing buildings where the design is already fixed, or when a building must meet many functional needs, e.g. a housing block which has a community garage, commercial premises, leisure activity rooms, etc.

The following list includes some critical situations which, in combination with poor sound insulation, may give rise to dissatisfaction and complaints (see also fig. 10.1):

- noisy rooms, like bathrooms and kitchens, adjacent to neighbouring bedrooms;
- staircases adjacent to bedrooms and living rooms;
- lift shafts located next to quiet rooms;
- commercial and equipment rooms located next to dwellings;
- equipment such as HVAC external units without noise enclosures or noise barriers close to windows or located in interior courtyards;
- technical rooms (heating, washing machines) next to living rooms and bedrooms;

- big windows and balconies facing noise sources like motorways, train tracks, etc.
- community garages and automatic garage doors located below dwellings.

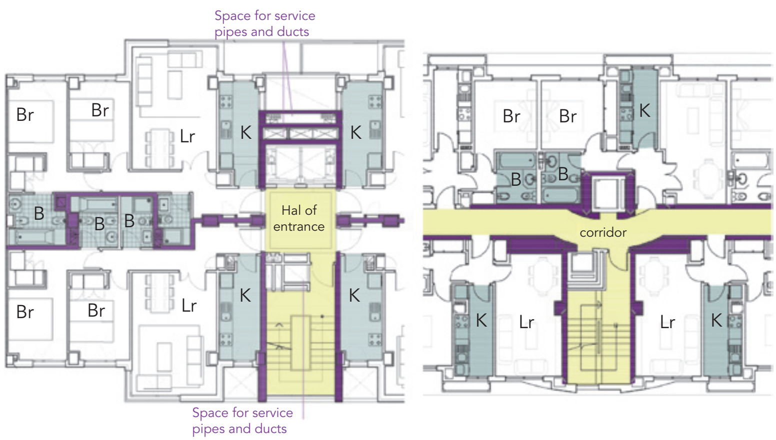


Figure 10.1. *Examples of acoustic favourable / unfavourable layout in buildings.*
Left*: Favourable design. Noisy areas (bathrooms, kitchens, stairs, lift) are grouped together. Corridors are buffer spaces between noisy and quiet areas.*
Right*: Unfavourable design: The stairs and the lift are adjacent to living rooms.*

When the layout of a housing block is not optimal, additional attention must be paid to sound insulation requirements, to the design of each of the separating walls and floors, and depending on the noise source, to noise barriers or noise enclosures.

10.2.2. Separating walls

When designing the right separating walls there are two aspects which must be considered:

- choosing the right partition to meet the requirements;
- designing the right junction details to avoid or minimize flanking transmission.

Some common design errors are:

- sound insulation properties of chosen structure below requirements;
- omitting the solid mass barrier in the floor build up at the line of the separating wall. (figure 10.2);
- insulating the cavity wall with a non-porous thermal material, for instance expanded polystyrene or PUR;
- lack of detailing or bad detailing, which results in dominant flanking transmission paths;
- thermal insulation lining on a concrete wall between heated and unheated rooms with wrong resonance frequency of the mass-spring-mass system;
- inner leaf of the external walls not interrupted in correspondence with the T junction with the partition walls;
- attic rooms: roof (ventilated or not) not interrupted in correspondence with the junction with the partition walls;
- electrical boxes made symmetrically (not staggered) on both sides of the wall;
- ventilation channels situated near each other in one cluster or unique ventilation duct for several floors (this reduces sound insulation between flats in different floors);
- flanking transmission via gypsum board, passing by the wall between dwellings (inner leaf of external wall bridges double stud wall reducing its acoustic performance);
- continuous foundation/lowest floor and no resilient interlayers (design error if high sound insulation performance is required);
- position of installations (sewage, water supply, mechanical installation HVAC) located between a wall/two walls of detached dwellings;
- use of timber separating floors with masonry supported walls (connection between two separate structures which do not have technical compatibility for sound insulation) leads to excessive flanking sound transmission, with 10 to 15 dB drop in performance for airborne sound insulation;
- use of ceiling consisting of a flexible layer on mineral wool in order to increase the airborne and or the impact sound insulation of floors; if the resonance frequency of the flexible layer is in the range of 50 – 80 Hz, it is possible to undermine the sound insulation at these frequencies.

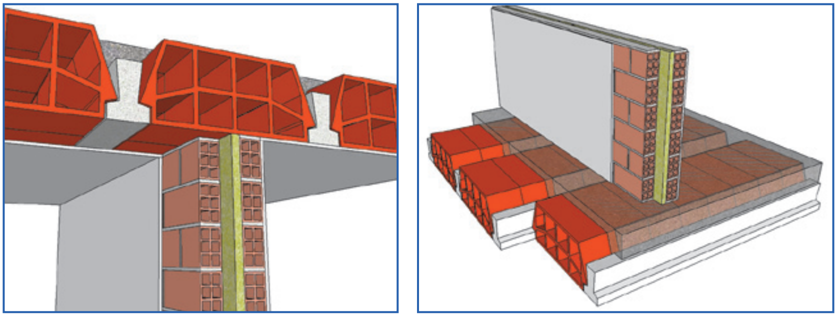


Figure 10.2. *No solid barrier in floor along wall line (left: parallel to wall, right: perpendicular to wall).*

Single heavy walls

This type of wall comprises concrete or limestone blocks with a weight of 400 to 575 kg/m^2. Flanking transmission has to be minimised with flexible junctions with other walls including the inner façade, but floors are rigidly connected to the partition wall. If the inner leaf of the façade is heavy (> 250 kg/m^2), the wall can be rigidly connected to it.

Heavy cavity walls

The following list gives guidance on heavy cavity walls, often composed of two masonry, concrete or limestone leaves (ca 200 kg/m^2) separated by a cavity at least 40 mm wide. In South European countries cavity walls with a lower weight are used based on clay blocks.

- place a porous fibre material in the cavity;
- control flanking transmission along floor, ceiling and abutting walls; if possible, keep the cavity uninterrupted from the foundations to the roof;
- the inner leaf of the façade must not bridge the two leaves of the separating wall; in addition, place a flexible cavity stop to interrupt the cavity, such as a mineral wool barrier;
- when the leaves rest on a continuous slab connecting different dwellings, elastic layers can be placed on top and bottom of each wall, as well as in the junctions with the abutting walls to reduce flanking transmission;
- place the separating wall on top of a beam, this reduces flanking sound transmission, especially if the floors are beam and block floors;

- make a shaft for drainage pipes or ventilation ducts in every dwelling;
- if drainage pipes or ventilation ducts are located between the two leaves of the separating cavity wall, design an enclosure to accommodate them which has a similar sound insulation of the separating wall.

Timber Separating Walls

Timber separating walls are commonly formed from pre-fabricated timber cassettes which are placed on site and then lined in-situ with plasterboard finishes. A typical wall is constructed from two panels separated by a cavity. It is common for mineral fibre materials to be placed within the stud cavity during the manufacturing process.

Some points to watch are:

- avoid connections between the two panels;
- avoid very small cavities (<50mm) between cavities which cause resonant problems at low frequency; it is better to have one cavity of 250 mm then three cavities of 50 or 90 mm;
- cavity dimensions can be confused by the addition of 'sheathing' boards for additional racking stability or for protection in transit;
- flanking transmission paths via the ground borne slab are controlled through the use of floating floor treatments or from a full break in the slab detail;
- provide sacrificial cavities for electrical services, therefore reducing the need for penetrations.

Light steel frame walls

Light steel frame walls or metal stud walls commonly consist of several gypsum based boards attached to two independent steel frames. They are most commonly used in multi storey developments where structural steel or concrete is being used although they are also popular in refurbishment developments of existing buildings.

Steel frames must not be connected. The thickness and type of studs depend on the height of the room. Avoid using structural ties by selecting the right studs.

Joint design greatly influences the sound insulation of walls. Attention must be paid to flanking constructions as the performance of steel frame walls is limited by the type of elements abutting to them and the connections between them. The following advice must be taken into account:

- steel partitions are commonly found in conjunction with pre-cast or cast in-situ concrete slabs, so detailing to reduce flanking via the slab is achieved with floating floor and ceiling treatments;
- timber base plates can be used at the bottom of metal stud partitions as they provide a defined edge for any screed that is to be installed and allow for the metal stud to be set above the line of the screed;
- the inner leaf of the external wall must not bridge the independent steel frame walls;
- detailing around either steel or concrete columns generally aims to ensure that plasterboard layers have minimal contact or connection to the primary structure.

Retrofitting existing walls

In most European countries, houses built during the first half of the 20th century had single leaf masonry separating walls which were often composed of clay bricks or concrete hollow blocks around 190 – 250 mm wide. The sound insulation values of these walls are often far below the current requirements of each country.

The following methods are common ways to improve sound insulation of existing masonry walls:

- rendering the separating wall, which will reduce sound leaks and is highly recommended prior to further treatments;
- applying mineral fibre backed boards to the existing wall;
- independent linings consisting of one or two layers of gypsum boards fixed to independent wood or steel frames; the independent linings must never make contact with the existing wall; the cavity must be filled with a porous absorbent material.

These treatments are not fully effective if flanking transmission via the adjacent walls such as the inner leaf of the façade is not controlled. In situations where flanking transmission is dominant, upgrading works to the separating wall make little or no difference. To avoid such transmission it may be necessary to install independent wall linings to the façade (see figure 10.3).

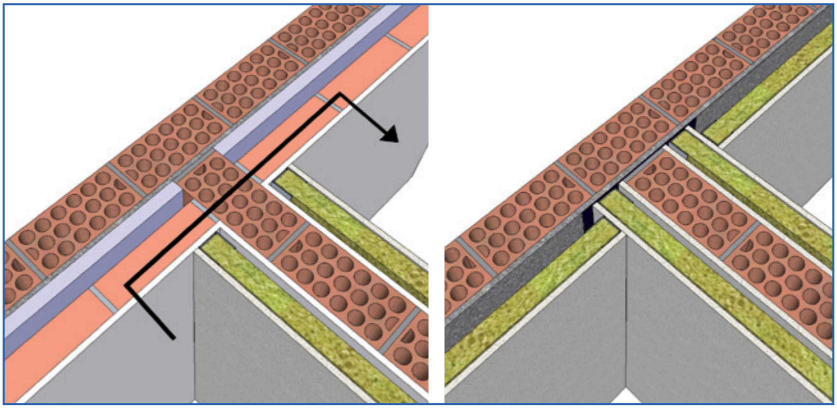


Figure 10.3. *Examples of independent linings applied to a separating wall and their performance. Left: No remedial treatment is done in the facade, so the flanking transmission via the existing brick inner wall is dominant,* $D_{nT,w} + C = 48$ *dB. Right: Remedial treatment is done in the façade,* $D_{nT,w} + C = 54$ *dB.*

10.2.3. Floors

Floors must provide both airborne and impact sound insulation. In designing floors, first the right floor must be chosen; secondly right junction details to avoid flanking transmission must be designed.

Heavy floors

Heavy floors are commonly formed by concrete slabs, precast slabs, grid floors or beam and block floors. Depending on their surface mass, their airborne sound insulation can be adequate, but their impact sound insulation needs to be improved. The best way to control impact noise is to specify a floating floor.

The following advice should be followed when designing a floating floor:

- design the screed for the load that is going to support; for housing loads, 50 mm of slab is often adequate, but in some countries the minimum thickness is 65 mm for a mortar screed and 50 mm for an anhydrite screed;
- select the resilient layer whose load bearing characteristics are adequate for the screed; the dynamic stiffness of the resilient layer should be between 8 and 20 MN/m^3;

- if the resilient material is not waterproof, use a waterproof layer to cover it so that when the cement screed is poured, moisture does not come into contact with the resilient layer or the base floor;
- avoid any rigid contacts between the screed and the surrounding walls, pillars and façades; place flanking strips in the joint between the screed and the surrounding walls; use the same resilient material as in the floating floor or 6 to 8 mm of foam;
- avoid any contact between the base floor and the floating floor and between the floating floor and the walls or façades;
- inner walls that are built upon the floating floor should not be rigidly connected to walls and façades that are built upon the primary structure;
- anchors (with screws) placed on the base floor must not be connected to the floating floor; place them *in* the base floor;
- plasterwork, wooden frames and skirting boards on walls and façades must not be in contact with the floating floor.

When planning, the following common errors may occur:

- stairs rigidly connected to the walls (impact noise from staircase to apartments);
- lack of a floating floor on the ground floor of multi-storey buildings; impact sound can also be transmitted horizontally through the slabs and noticed in adjacent rooms; whenever there are quiet rooms, even if they are located on the ground floor, a floating floor should be considered; it is also possible to separate the ground floor from the foundation and the partition wall with flexible layers;
- lack of a floating floor in row houses which have a continuous slab that connects each dwelling (this error could lead to very bad performance in horizontally impact sound); in the case of cavity walls with a cavity from top till bottom, if the impact sound insulation of the first and second floor is LnT;A < 42 dB: a floating floor is not needed.

Single heavy floors

Single or solid floors are made of concrete and a top layer of screed or anhydrite. For a good sound insulation the screed must be directly glued to the base floor. Special techniques are used such as a special cement layer for screed and compound spray for anhydrite values of 800 kg/m^2 is necessary for $L_{nT;A}$ < 54 dB, 600 kg/m^2 for $L_{nT;A}$ < 59 dB.

Timber lightweight floors

In timber based buildings, the bearing construction consists of wooden bars with a dry floating floor on top and a uncoupled ceiling with double gypsum board (12,5 mm). In the cavity there is at least 100 mm mineral wool. Sometimes a screed is used to improve the thermal capacity of the dwelling and therefore the sound insulation. This floor construction is often used also in renovations.

Whenever timber floating floor systems are timber battens or cradle systems, the incorrect specification of cradle and batten systems can result in failures on site. It is important that the correct depth of system is used as well as the correct system type.

10.2.4. Façades

In most countries, exterior walls are typically heavyweight cavity walls where thermal insulation is placed in the cavity. In these cases, the sound insulation of the façade is limited by the sound insulation of the windows and air inlets.

When specifying a window, consider the following advice to reach the required sound insulation value:

- glazing: insulating glass units can improve their sound insulation if the two glass panes have different thickness and one of them is laminated;
- the ventilation grids, if present, should have a sound attenuation;
- frame: the material of the window does not have much influence on its acoustic performance, but sliding windows usually provide less sound insulation than casement windows; proprietary frame systems may provide the sound insulation required;
- secondary glazing or coupled windows are usually the best cost efficient way of significantly reducing the noise intruding in existing buildings.

10.2.5. Service equipment noise

Some noise problems are related to service equipment, especially airborne and structure-borne sound coming from bathrooms and kitchens located upstairs. In the design of service equipment, consider the following:

- all plumbing components should be isolated from the building structure; a resilient material such as fiberglass or polyethylene should be used wherever the pipes penetrate walls and floors; in addition, it is vital to seal the perimeter of any penetration;

- drainage pipes should be specially designed acoustic pipes or be insulated to avoid airborne noise; if possible, drainage pipes should run only in vertical direction; if drainage pipes run horizontally in the ceiling void, a suspended, insulated and sealed ceiling will be required;
- fixtures can be set on resilient pads, especially the bathtub and shower pan to avoid the radiation of water splash noise transmitting to the houses below.

10.3. Workmanship: common errors and good practice

In order to provide acoustically more robust constructions, the knowledge of good and bad practices and the possible influence of workmanship is also of primary importance. Bad practice and workmanship may lead to very different results from those expected in the design phase. This could happen not only because of errors but also because the construction details may not have been clearly defined or may have been misunderstood.

Therefore, during the design phase, it is important to define the best technological solutions that will ensure good acoustic design, but it is also important to make it easy to understand the details and the procedures. In addition, a failure to consider the impact of changes to non-acoustic issues can have a significant effect on sound insulation.

Another important issue to consider is the difference between the way a partition is built in the laboratory and in the field, which may lead to different results from those expected using laboratory data and models. A typical example is the cavity wall with horizontal hollow bricks; this type of wall has shown good laboratory results but frequently very bad in situ results. In fact, a typical workmanship error is the lack of mortar in vertical joints, leaving partially filled joints between blockwork. Therefore, it is always important to check that the technological solution chosen in the design phase is what will actually be built.

Looking at the typical workmanship errors reported in the different European countries, it is shown that most of the problems happen because the contractor or the builders do not understand the basic concepts of the acoustic performance of buildings but also because, as said above, builders construct in a way that may not reflect the detailed drawings. This may be due to the fact that the detailing issued is insufficient or because detailing has not been issued to those working on site.

In this paragraph a summary of good and bad practices and effects of workmanship, with a draft list of typical errors, has been included. In addition, section 10.4 illustrates with drawings and photos further examples of good and bad practice and common errors in design and workmanship.

10.3.1. Typical examples of construction errors for airborne sound insulation

Variability of results due to workmanship depends mainly on the difference between the way a partition is built in the laboratory and in the field and on the incorrect implementation of joints, connections between equipment and partitions. The wrong use of a technical solution or the damage of materials could also lead to bad sound insulation performances. The most typical construction errors reported in the different European countries are:

- lack of mortar in vertical joints, leaving partially filled joints between blockwork for walls that require mortar also in vertical joints (figure 10.4);
- insufficient plaster layer (not following manufacturers' guidance);
- gaps above masonry wall or cracks in the wall (acoustic leakage);
- sound absorbing material not continuous in the cavity of cavity walls;
- tears in the sound absorbing material inside the cavity of cavity walls due to service zones or pipe chases: the subsequent filling with mortar may create a bridge between the two leaves of the cavity wall;
- pipe chases for building services not properly filled with mortar;
- lack of plaster on one side of the cavity in the cavity wall when prescribed in the chosen technical solution;
- incorrect installation of elastic interlayer on top of double walls;
- incorrect resilient layer, used as isolation mechanism in "wall-floor" junctions, under single heavy walls (risk of crushing of resilient layer);
- hard connection between the two walls initially designed as disconnected walls;
- incorrect wall ties used in separating walls designed with a specific dynamic stiffness requirement for the tie;
- leakage via cavity if rigid insulation is used in junction instead of soft thermal insulation (and presence of windows);

- collection of mortar at base of cavity wall (at ground floor), creating a strong acoustic bridge: the cavity of a cavity wall should be kept clean;
- in timber-based separating walls, the cavity between the twin stud can often be viewed by the builder as an area where errors in build tolerances can be rectified; this can result in the total cavity depth being reduced as stud locations are shifted to accommodate build errors; this can reduce the overall performance of the partition dramatically;
- leaving timber structures exposed for prolonged periods during high rainfall can result in bowing of the sheathing panels and thus reduce overall cavity depth; the use of water repellent membranes can reduce this issue;
- higher thermal performance requirements have resulted in a move towards the use of rigid insulation materials in timber frame where traditionally mineral fibre quilt was previously used; this can lead to the incorrect assumption that rigid insulation for party walls also provides a sound insulation function.

Figure 10.4. *Examples of lack of mortar in vertical joints between blockwork.*

10.3.2. Typical examples of construction errors for impact sound insulation

Impact sound insulation is very sensitive to workmanship, particularly for floating floors. Good practice procedures for floating floors have already been listed in paragraph 10.2. In relation with the construction errors, the basic rule for floating floors is to avoid any contact between the floating floor and the internal walls or façades or the base floor. Therefore, the main errors for impact sound insulation are:

- skirting board in direct contact with flooring;
- floor tiles in contact with walls;

- perimeter resilient band not properly adherent to the walls and consequent presence of mortar between the band and the walls;
- perimeter resilient band too short or cut before the placing of the flooring;
- perimeter resilient band not continuous, especially in corners;
- rigid contact between the tiles or the floating mortar and the French window marble doorstep;
- lack of structural separation between the floating mortar in correspondence of the door of the rooms;
- floor surface below the resilient material not perfectly flat or not properly cleaned (presence of brick or iron pieces, cables, etc);
- tears in the resilient material of the floating floor, and resultant breeching of floating mortar to the structural floor;
- presence of pipes not fully embedded into the lightened mortar (under the resilient material);
- problems with bathroom floors (tiled floors and walls, many pipes, etc);
- insufficient insulation of heating pipes from sand/cement screed or incorrect fixation of heating element (sound bridges between screed and concrete slab reducing impact sound insulation between flats);
- incorrect fixing of resilient bar with ceiling fixing screws (the screws should not touch joists);
- wrong installation of ceiling causing sound bridges (reduced effect of the resilient mounting);
- in timber batten floating floor systems, battens placed incorrectly (e.g. placed the wrong way up, or at the wrong centers);
- in timber floors, the correct installation of flanking strips can often be overlooked; isolation of the floating floor from the wall structure as well as isolation of the skirting board from the floating floor are equally important.

As an example of the influence of workmanship on the impact sound insulation of a floating floor, with measurement before and after repair, the case of the French window doorstep area is illustrated (figures 10.5 and 10.6). During the first measurement, a high amount of noise coming from the French window area was heard in the receiving room. Thus the first row of ceramic tiles and a small part of the floating mortar near the French window doorstep were removed (figure 10.5): the main problem of noise transmission was due to the lack of the perimeter resilient band under the

French window that caused a rigid contact between the tiles and part of the floating mortar with the marble doorstep of the French window itself. Once the builders solved the problem, placing the perimeter resilient band up to the marble doorstep, a second measurement was carried out, by the same operator, with the same equipment and using the same positions of the impact generator and microphone.

The comparison is shown in figure 10.6. The impact sound insulation index $L'_{n,W}$ improved by approximately 10 dB (from 70.2 dB to 60.6 dB). The decimal places for the indexes were used only for comparison. In terms of frequency comparison the main differences were at high frequencies, with improvements of up to 12 dB. The floating floor provides good performance only if properly installed. Even a small perimeter section not properly realised (in this example the rigid contact affected a length of 140 cm) could significantly reduce the acoustic performance of the whole floating floor.

Figure 10.5. *View of the French window area with the first row of tiles and floating mortar removed (on the left) and after the repair (on the right).*

10.3.3. Typical examples of construction errors for façade sound insulation

For façade sound insulation, construction errors depend mainly on the correct installations (position and setting) of the windows, as well as on the type and material of the rolling shutter box. Frequently the laboratory data relates to the windows without the rolling shutter and the solution adopted for the whole system is not checked before the installation. Another important factor is related to the connection between the windows and the walls (sealing, dimensions, etc). The main errors are:

- fine setting of doors and windows not made or made incorrectly;
- opening between a rolling shutter and the external wall too wide and/or lack of brush between the rolling shutter and the external wall;

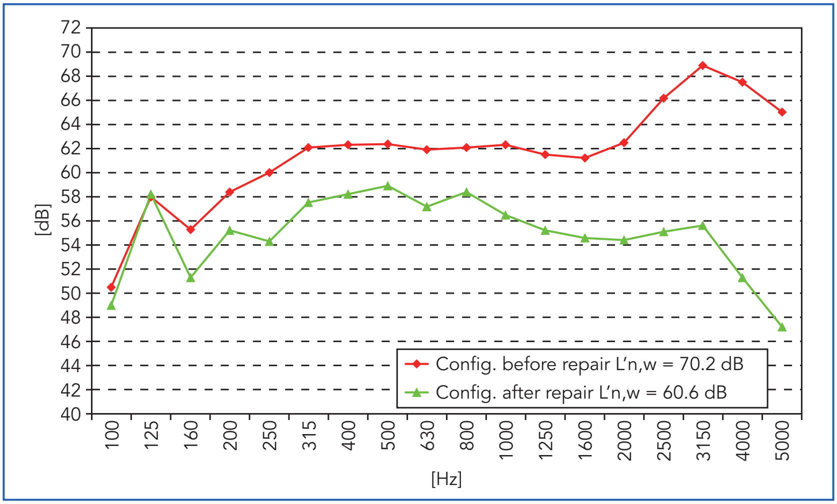


Figure 10.6. *Frequency comparison between the floating floor before and after the repair (see figure 10.5) (decimal places for the indexes used only for comparison).*

- rolling shutter box sides too light and/or absence of sound-absorbing material inside the box or rolling shutters with the box embedded in the wall;
- rolling shutter box incorrectly connected to the wall (presence of gaps between the rolling shutter box and the wall);
- lack of sealing in some areas between the frame and the counter-frame, hidden by window profiles;
- lack of mortar in some areas between the counter-frame and the walls, hidden by window profiles;
- counter-frame empty inside (lack of foam or sound-absorbing material);
- contact areas between glass and window shutter not properly sealed.

As an example of the influence of the fine setting of the windows, results of measurements made before and after the intervention are reported in figure 10.8. The main acoustical defects detected on the window before the correct setting were the presence of chinks between the shutters (figure 10.7) and the fixed frame and an opening in the central locking mechanism. After a careful setting these problems were solved, and the performance of the façade improved of approximately 4 dB ($D_{2m,nT,W}$ from 35.6 dB to 39.0 dB, figure 10.8). The greater improvement (up to 12 dB) was observed at medium frequencies. The complete study included approximately 20 façades, measured before and after the fine settings obtaining an average difference of approximately 7 dB.

Figure 10.7. *Details of the main windows defect (left picture) and detail of window fine setting (right picture).*

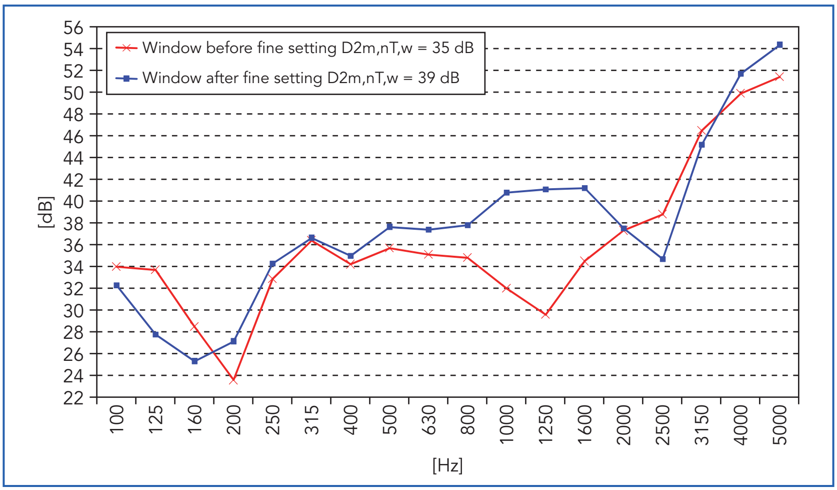


Figure 10.8. *Frequency comparison of a façade before and after the window fine setting.*

10.3.4. *Typical examples of construction errors for service equipments*

For service equipments, good practice in design and workmanship frequently depends on the same rules, mainly related to the avoidance of structure-borne sound caused by rigid connections between the noise and vibration sources and the structures. As a consequence, most of the construction errors depend on the lack of knowledge or consideration of builders. Further suggestions to those already listed in paragraph 10.2 are:

- waste water pipes embedded in mortar: lack of acoustic insulation material around the pipes next to the floor, walls or next to other pipes (figure 10.9 left);
- water supply pipes without acoustic insulation material (acoustic bridge);
- tears of the acoustic insulation material surrounding the pipes, especially in areas of other pipes engagements;
- connection between waste water pipes and walls made with rigid anchorages (fixing clamps);
- waste water pipes passing through quiet areas without acoustic insulation material;
- lack of sound-absorbing material inside the cavities;
- changes of direction in waste water pipes (figure 10.9 right);
- no acoustic silencers in ventilation systems.

Figure 10.9. *Waste water pipes embedded in mortar (left). Changes of direction in waste water pipes (right).*

10.3.5. Checklist as a good practice procedure

Considering the long list of design and workmanship errors, which are an important source of variability in in-situ performance, it is necessary to address this aspect very carefully. In order to avoid mistakes and provide more robust construction designs to achieve their required sound insulation performance levels, the use of checklists is a very important and useful procedure. Spain, Belgium and the UK have checklists but the procedures are not mandatory. Other countries, like Romania, Slovenia and Sweden, have specific procedures to check documentation and on-site verification. The Netherlands have an attention list. Switzerland has a checklist for service equipment but only for Minergie label (private).

10.4. Further examples of good practice and common errors in design and workmanship

10.4.1. Foreword

This paragraph contains additional images with examples of good practice and common errors in design and workmanship which affect sound insulation performance.

This collection of images is based on the work presented by COST TU0901 members in the WG3 sessions held during the action. It shows different techniques and constructions all around Europe.

In some cases, the decrease in sound insulation between good and bad workmanship/design will be given. According to the proposed acoustic classification scheme described in Chapter 5, a variation of 4 dB results in one class lower both for airborne and impact sound insulation.

10.4.2. Separating walls

10.4.2.1. Masonry walls

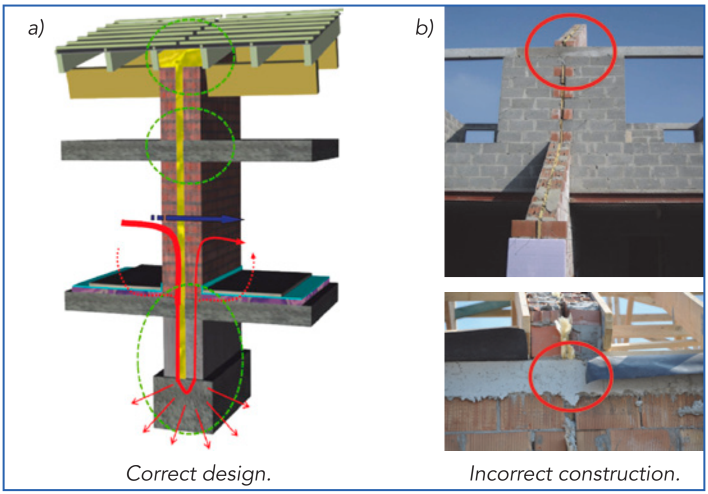


Figure 10.10. *a) Example of good design for row houses. Separating walls must be structurally and acoustically separate. The cavity does not have any bridges and must be continuous from the foundations to the roof. The green circles indicate the key junctions where bridges have to be avoided. b) Incorrect workmanship. Mortar connects both leaves of the wall. (The decrease can vary from 3 dB to 12 dB, depending where and how many bridges can be found within the cavity wall).*

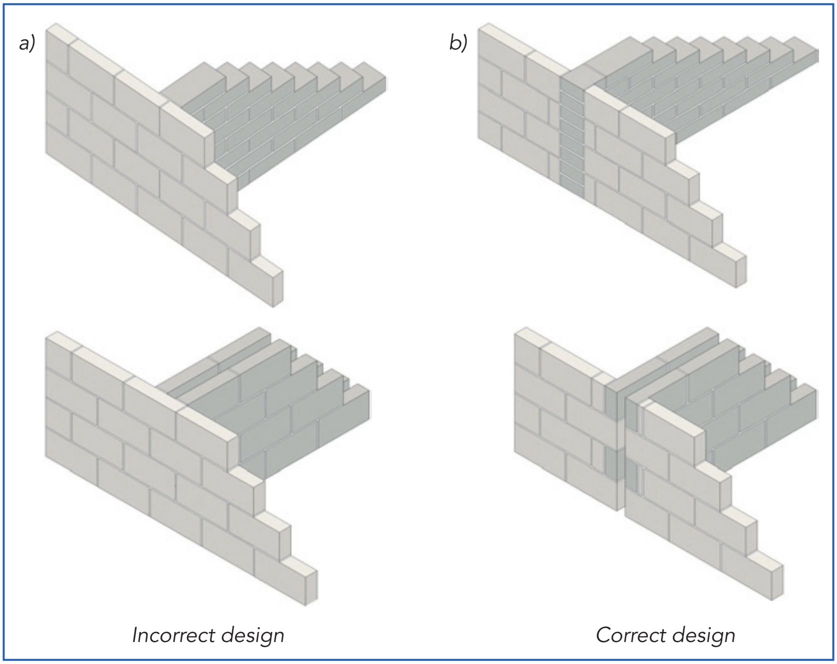


Figure 10.11. Incorrect specifications or a lack of specifications of design detailing often lead to flanking transmission. a) Incorrect detailing. Continuous inner leaf of external cavity walls. This leads to excessive flanking sound transmission, with 8 to 10 dB drop in performance for airborne sound insulation. b) Correct design. There is a break in the external wall inner leafs.

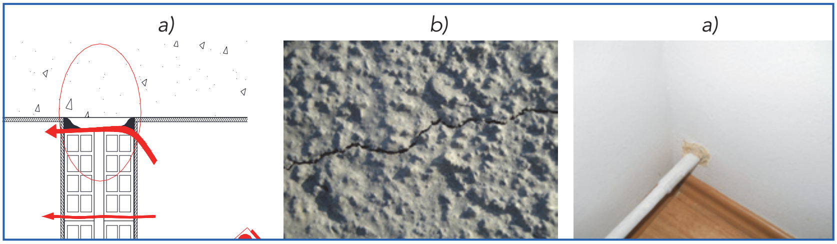


Figure 10.12. Some typical errors in design and workmanship which lead to a decrease in airborne sound insulation. a) Sound leakage through the top of a masonry wall due to lack of mortar in conjunction with very thin layers of plaster. (3 to 6 dB depending on the length of the weakness) b) Acoustic leaks due to cracks in the walls (3 to 9 dB).c) Heating Pipes passing though the separating walls in retrofitted housing. (3 to 6 dB lower).

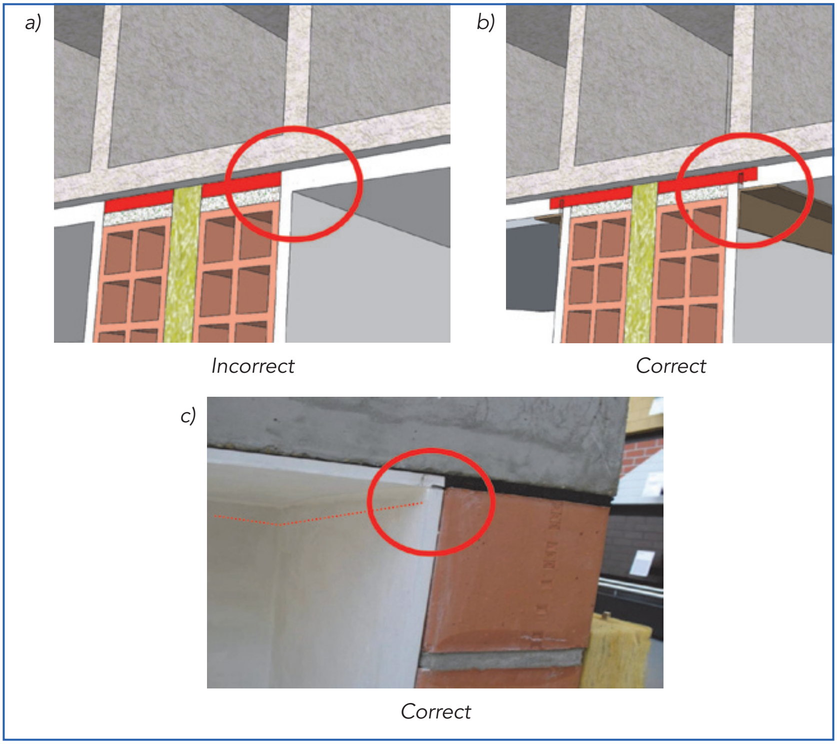
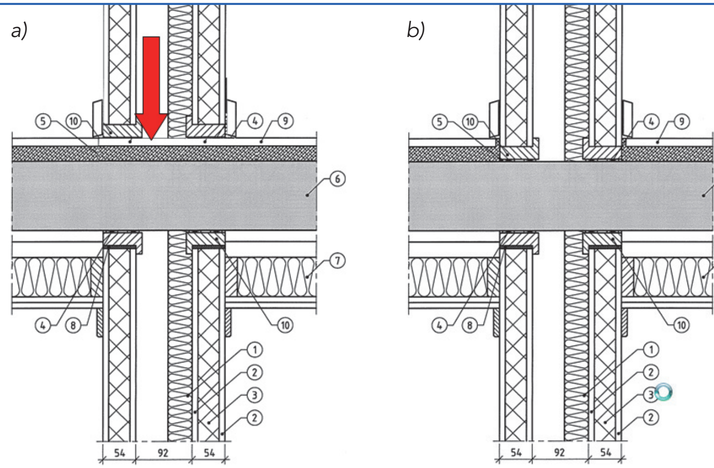


Figure 10.13. *In some cases, elastic layers are placed on top of cavity separating walls to limit the flanking transmission along the floor and ceiling. When this is the case, the connections between the plaster finishes of the walls and the ceiling above must be avoided. a) Typical separating walls in Spain. Incorrect workmanship. The plaster finish of the wall bridges the ceiling. b) Correct design. The elastic layer is larger than the brick, and a cut is performed in the plaster finish. A paper band is used prior to painting the wall. The difference between good and bad workmanship can be up to 5-6 dB. c) Belgian example showing the disconnection of plaster finishes. An elastic sealant is applied along the joint.*

10.4.2.2 Light steel frame walls



Incorrect design | Correct design

1. 40 mm mineral wool
2. 9 mm plasterboard
3. Straw ca 360 kg/m^3 ca 36 mm
4. Resilient Band
5. Elastic layer
6. Concrete floor 250 kg/m^2
7. Free hanging ceiling
8. One component PUR
9. Floating floor
10. Timber sole plates

Figure 10.14. a) Incorrect detailing. The metal studs are fixed to the mortar screed, which is continuous between apartments. b) Correct design. The floating floor is not continuous between apartments. a) results in about 13 to 17 dB worse impact sound insulation and around 4 to 8 dB lower airborne sound insulation than b).

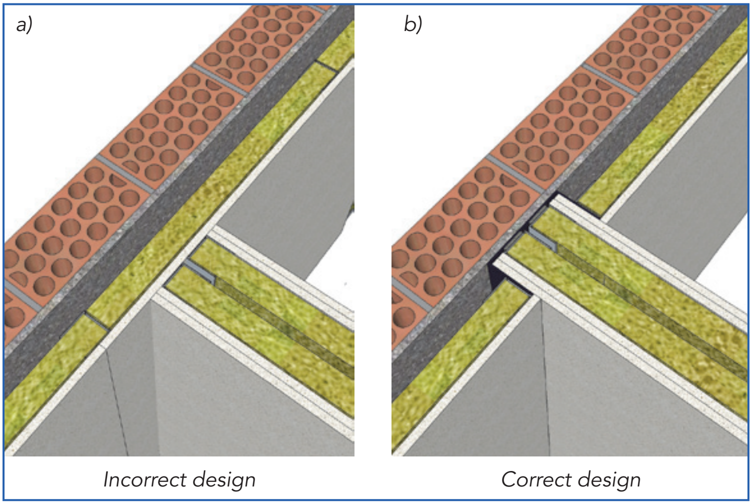


Figure 10.15. a) Incorrect wall-façade junction detail. The inner leaf of the external wall bridges both C studs of the double steel frame wall. The red arrow shows the flanking dominant transmission path. b) Correct design.

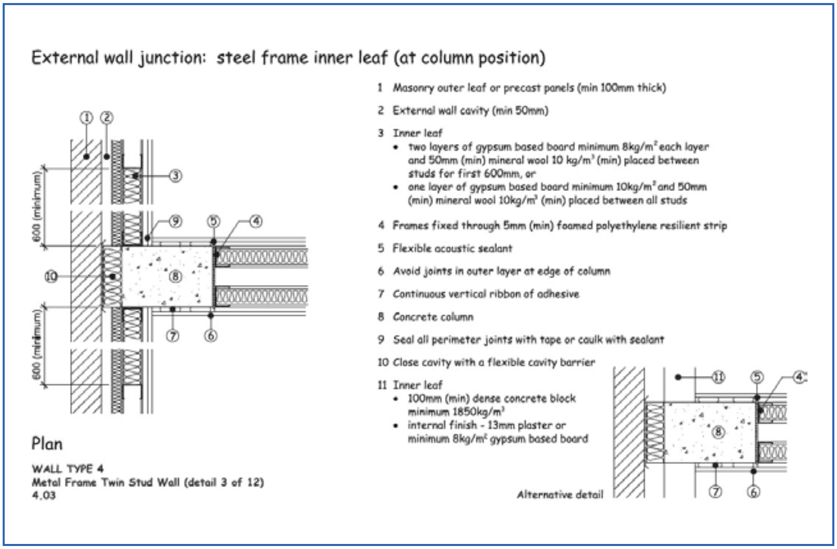


Figure 10.16. Example of external wall junction. Correct detailing around either steel or concrete columns. Plasterboard layers must have minimal contact or connection to the primary structure.

10.4.2.3 Timber separating walls

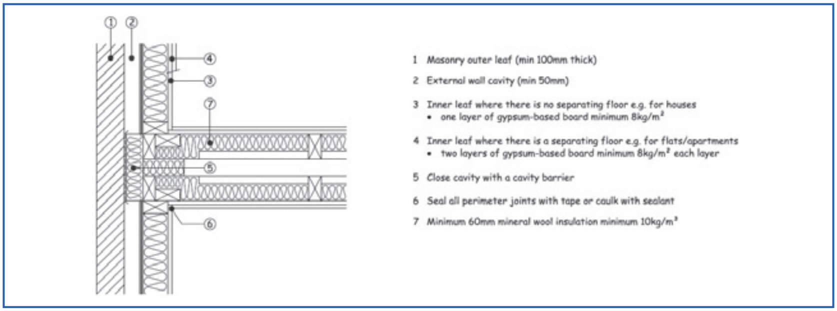


Figure 10.17. *Example of correct separating wall – façade junction detail. The inner leaf of the façade is interrupted by the separating wall.*

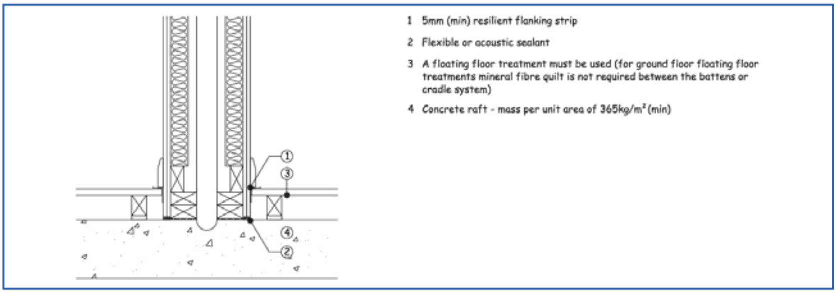


Figure 10.18. *Cross section through a timber separating wall showing raft foundations. Flanking transmission paths via the ground borne slab are controlled through the use of floating floor treatments or from a full break in the slab detail.*

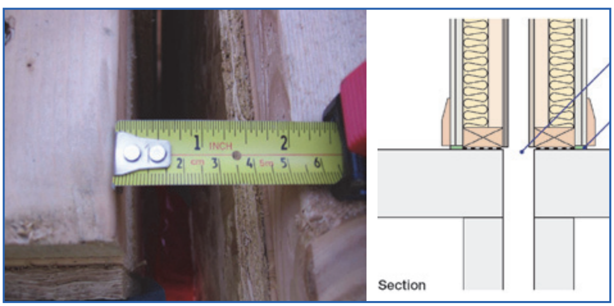


Figure 10.19. *Example of common error when building timber separating walls. The total cavity depth is reduced as stud locations are shifted to accommodate build errors. This can reduce the overall performance of the partition.*

a) b)

Figure 10.20. *a) Leaving timber structures exposed for prolonged periods during high rain fall can result in bowing of the sheathing panels and thus reduce overall cavity depth. The use of water repellent membranes can reduce this issue. b) Inappropriate use of rigid insulation for party walls.*

10.4.3. Separating floors

10.4.3.1. Heavy floors

a) b)

Incorrect *Correct*

Figure 10.21. *a) Example of a bad installation of flanking strips of a floating floor. Perimeter resilient strips are not continuous in corners, too short and not properly fixed to the walls. This can result in connections between the screed and the surrounding walls, which will decrease sound insulation performance. b) Example of good installation of resilient layer prior to pouring a screed. As seen, the impact insulation layer is continuous; corners are covered with the resilient layer, which is long enough to be over the screed level after pouring the mortar.*

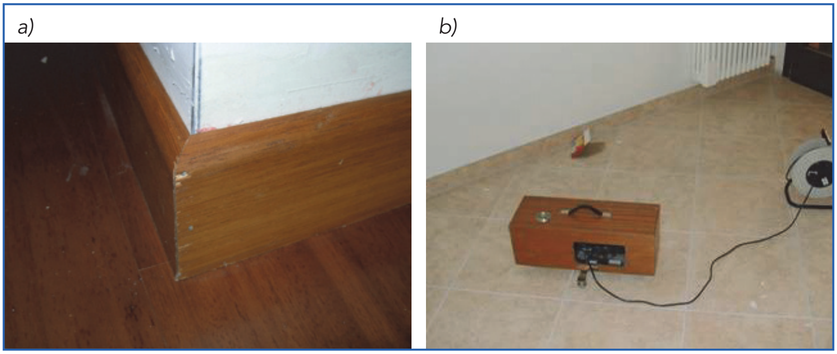


Figure 10.22. *Examples of skirting boards directly fixed to the walls. To ensure impact insulation performance, the skirting board must not bridge the walls and the floating floor. See chapter 10.3.2.*

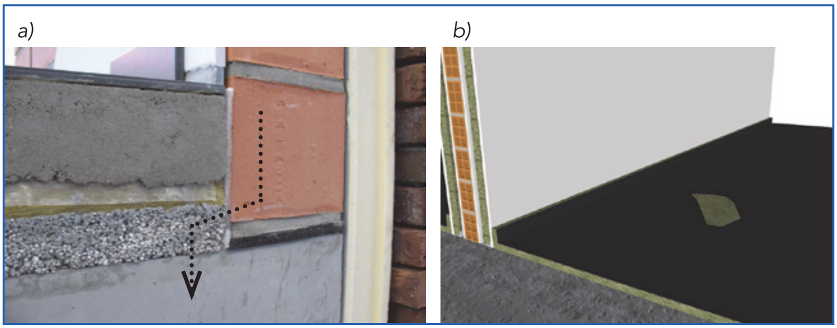


Figure 10.23. *a) Flanking strips must separate the floating floor from the walls. In addition, when resilient layers are placed below the separating wall, flanking strips must be used to separate any level screed installed under the floating floor to avoid any possible transmission path such as the one shown in the red arrow. b) Bad installation of an elastic layer, which is punctured due to dirt, debris, etc.*

a) b)

Incorrect Correct

Figure 10.24. *a) Stairs are rigidly connected to the walls, resulting in the transmission of impact noise to the adjoining premises.*
b) Example of a decoupled staircase. Building Regulations in some countries limit the transmission of impact sound between stairwells and dwellings.

10.4.3.2. Lightweight timber floors

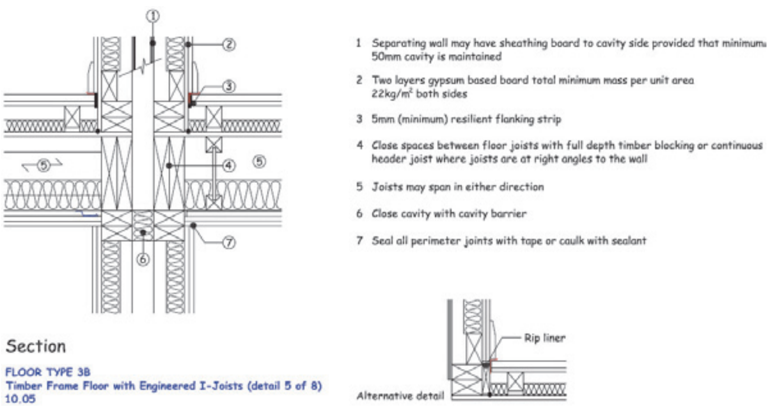


Figure 10.25. *Example of a timber frame floor with Engineered I – joists.*

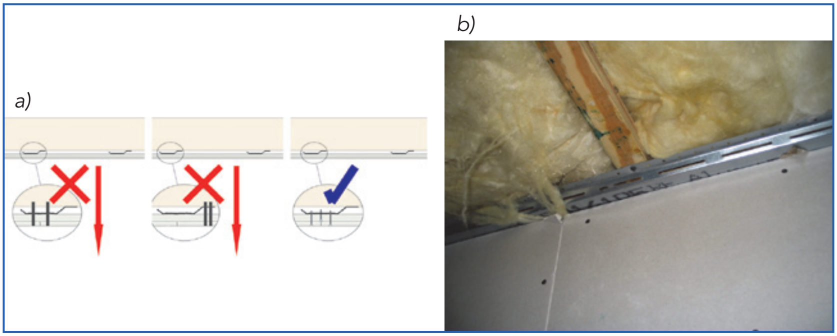


Figure 10.26. *a) Example of correct and incorrect fixing plasterboard to resilient bars. Ceiling fixing screws should only penetrate resilient bar and not touch joists. b) Bypassing of resilient bar or placing wall linings hard against resilient bars will reduce their effectiveness.*

10.4.4. Façades

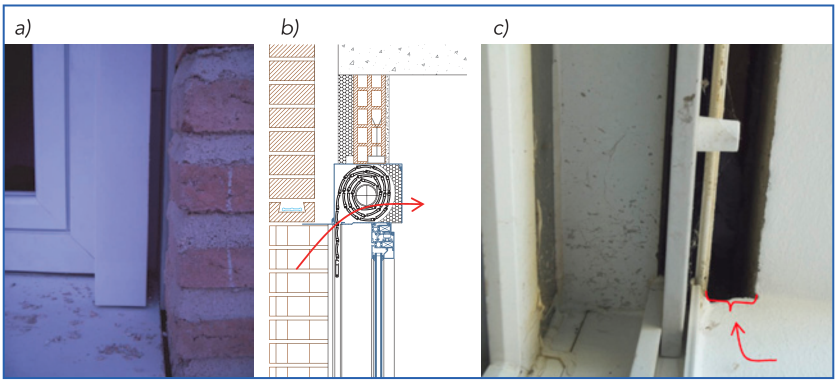


Figure 10.27. *Cracks and unsealed gaps enable sound to enter a building. a) Excessive gap left between the window frame and the façade wall. b) Common detail of rolling shutter showing sound path. c) Excessive opening between the rolling shutter box and the external wall.*

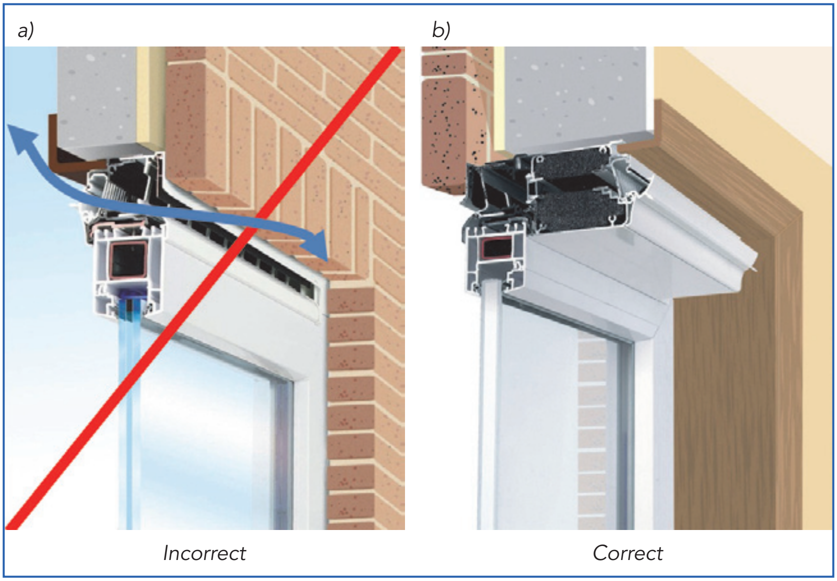
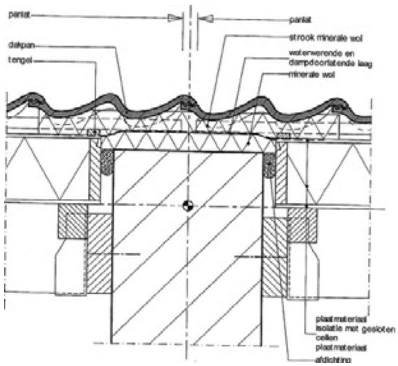


Figure 10.28. a) Indirect sound transmission via non-attenuated glazed-in ventilators. b) Sound absorbing window ventilators. The decrease in performance varies from 5 to 7 dB.

10.4.5. Roofs

Figure 10.29. No mineral wool sound barrier above partition wall in combination with roof elements with rigid thermal insulation (PUR, PIR, EPS) leads to a decrease of 5 – 10 dB in airborne sound insulation between rooms.



Tile lath with a break of at least 20 mm
Mineral wool sound barrier
Waterproof vapour open layer
Mineral Wool against Thermal bridge

Wood or chipboard 3, to 12 mm
PUR, PIR or EPS
Wood or chipboard 3, to 12 mm

One component PUR

Figure 10.30. *Cross section of roof construction of 10.29 and the position of the mineral wool barrier (600 mm long , 50 mm high and broad: The distance between two tile laths) The aim of the barrier is to improve the sound insulation through the cavity between the roof tiles and the roof element.*

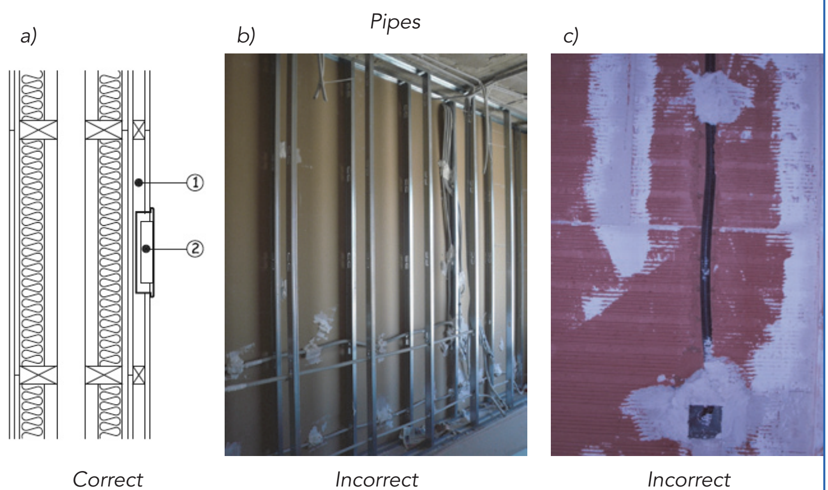


Figure 10.31. *a) Plan view of a timber frame wall, where a service void (1) is provided on surface so that services (2) do not puncture the primary wall linings. b) Example of bad installation of pipes inside the cavity of a metal steel frame wall. As seen, pipes are attached with plaster to the plasterboards. c) Chases performed in clayblock walls must be filled with mortar or a similar heavy sealing material. The photo shows chases performed in a wall made of lightweight ceramic blocks, weighting 80 kg/m², which have not been filled completely with mortar.*

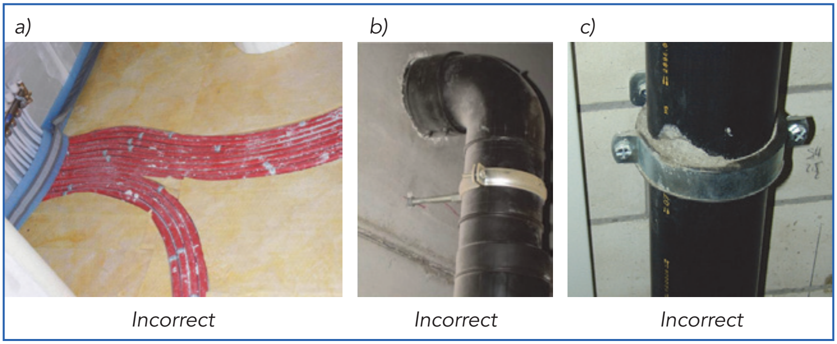


Figure 10.32. *a) Incorrect design of heating pipes going through the resilient layer of the floating floor. There is a risk that these pipes bridge the mortar screed and the partitions. b) Unsealed pipe penetrations lead to airborne noise transmission between rooms. As seen in the photo, this penetration is not properly sealed. A good sealing is also necessary for fire protection see also 10.33 c) Example of rigid connection between the pipe and the walls due to careless workmanship: mortar bridges the pipe and the hanger, so that noise is transmitted to the wall via the hanger, even when the pipe hangers have rubber pads.*

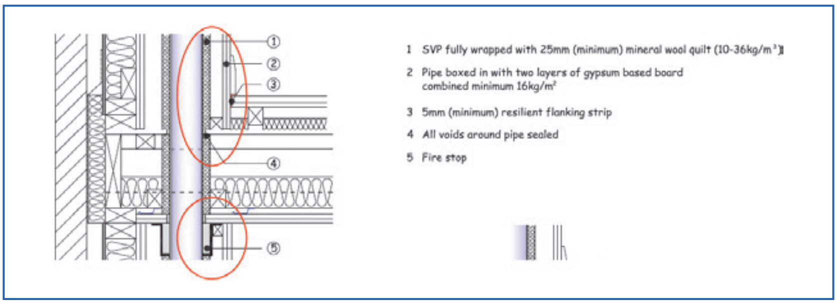


Figure 10.33. *Examples of service penetrations through timber floors. A separate timber frame, (in red, in the figure) is installed around waste pipes, which are lagged with mineral fibre quilt. The frame is then lined with plasterboard. This is intended to reduce the risk of sound transfer and the spread of fire.*

10.5. References

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EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

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Building acoustics throughout Europe
Volume 1: Towards a common framework in building acoustics throughout Europe

11

Design and Acoustic Performance of Building Constructions for Multi-Storey Housing: Compendium

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CHAPTER 11 Design and Acoustic Performance of Building Constructions for Multi-Storey Housing: Compendium

11.1. Introduction

This chapter provides an overview of the range of construction types found across Europe to meet various sound insulation requirements for separating (party) walls and floors. The typical construction system, material properties and key influencing factors are described.

The historic nature of sound insulation regulations in each country has led to developments in improvements to the types of constructions. More recently with the advent of stronger sustainability measures and resource efficiency of materials many countries have seen an increase in the use of light-weight structures, such as using timber frame.

The chapter provides details on typical performances for a variety of acoustic descriptors and is a useful reference chapter for architects, acousticians, house-builders, researchers and government departments or local authorities dealing with building standards for sound insulation in housing.

Detailed information on acoustic performance of typical building solutions found all around Europe, can be found in volume 2 of this e book, where the 29 European COST TU0901 countries (plus Australia and New Zealand) have included a specific chapter, which will be referred to as "Country Chapters" hereinafter.

11.2. Compendium of acoustic performance of walls & floors

The typologies of walls, floors and facades built in different European countries are very different from each other and this causes a significant spread in the acoustic performances of buildings.

In particular, the differences are large when comparing countries of north-central and southern Europe. Some examples of typical walls, floors and joints between components in different countries are shown in section 11.3.

Tables 11.1, 11.2 and 11.3 compile data for airborne and impact sound insulation of typical walls and floors found around Europe.

All the data shown in Tables 11.1, 11.2 and 11.3 concerning countries' typical solutions and performance are self-reported by COST TU0901 representatives from each country. The translation of the country descriptor to $D_{nT,A\ (50\text{-}5000\ Hz)}$ in tables 11.1 and 11.2 has been performed based on the equations described in Chapter 4. The figures cannot be considered exact, but rather a good estimation.

Table 11.1 shows in-situ airborne sound insulation data collected from twenty-two countries and focuses specifically on the typical separating walls currently being built involving solid blocks and cellular (hollow) clay blocks, single or double walls. The frequency range for the single weighted values shown is primarily 100 Hz to 3150 Hz.

With reference to masonry walls, the total width of the separating partitions between adjoining dwellings varies from 150 mm to 370 mm.

The performance range is from $D_{nT,w}$ 49 dB to 62 dB, with other values in terms of field sound reduction index R'w. Noticeably the performance of these constructions is not always relative to their width or mass per unit area. This is primarily due to flanking sound transmission via the external walls and their junctions with the party wall leaf. In some countries the external wall is not "interrupted" at the junction with the separating wall. This continuous inner leaf (or external wall) can reduce significantly the performance.

Table 11.1. *Example of current typical separating wall construction using block, clay and concrete in different countries (typical values supplied by TU0901 members).*

Country	Wall Description	Approx. Total Width [mm]	Typical Airborne Sound Insulation		
			Country descriptor (100-3150 Hz)	D_{nTw} (100-3150 Hz)	D_{nTA} (50-5000 Hz)
Austria	250 mm cellular clay block, lined with 70 mm mineral wool backed gypsum board on dabs o/s and plaster o/s	340	D_{nTw} 61 dB	61 dB	59 dB
Croatia	20 mm plaster + 210 mm reinforced concrete + 20 mm plaster	250	R'_w 53 dB	52 dB	51 dB
Czech Republic	15 mm lime plaster, 250-300 mm hollow bricks, 15 mm lime plaster	280-330	R'_w 53 dB	52 dB	51 dB
Denmark	200 mm concrete	200	R'_w 55 dB	53 dB	53 dB
France	180 mm thick concrete	180-300	$D_{nT,w}+C$ 53 dB	53 dB	53 dB

Country	Wall Description	Approx. Total Width [mm]	Typical Airborne Sound Insulation		
			Country descriptor (100-3150 Hz)	D_{nTw} (100-3150 Hz)	D_{nTA} (50-5000 Hz)
Germany	240 mm brick (density equal or greater 2.000 kg/m³), plastered b/s + 15 mm plaster	270	R'_w 53 dB	52 dB	51 dB
Iceland	200 mm on site concrete	200	R'_w 56 dB	56 dB	54 dB
Italy	2 x 120 mm cellular clay block (cavity wall) with 40mm cavity filled with mineral wool and lined with 15mm plaster b/s	300	R'_w 53 dB	52 dB	51 dB
Lithuania	2 x 100 mm cellular clay blocks (cavity wall) with 100 mm cavity and finished with 20 mm plaster b/s	340	D_{nTw} 56d B	56 dB	54 dB
Macedonia	2 x 120 mm cellular clay block (cavity wall) with 50 mm cavity filled with mineral wool and lined with 30mm gypsum	350	R'_w 53 dB	52 dB	51 dB
Netherlands	120 mm limestone - 60 mm cavity - 120 mm limestone	250-300	R'_w+C 54 dB	55 dB	54 dB
Norway	200 mm on site concrete	200	R'_w 55 dB	53 dB	53 dB
Poland	240 mm calcium silicate wall, plastered on both sides with 10-15 mm thick gypsum plaster	260	R'_w+C 51 dB	53 dB	52 dB
Portugal	2 x 150 mm cellular clay block (cavity wall) with 40 mm cavity filled with mineral wool and render/plaster lining to walls.	370	$D_{nT,w}$ 50dB	50 dB	49 dB
Serbia	150 mm on site concrete	150	R'_w 54 dB	54 dB	52 dB
Slovakia	200 mm reinforced concrete wall	200-240	R'_w 58 dB	57 dB	55 dB
Slovenia	200 mm reinforced concrete wall, with 50 mm aerated autoclaved concrete and 10 mm plaster finish.	260	R'_w 57 dB	57 dB	55 dB
Spain	80 mm cellular clay block (cavity wall) with 40 mm cavity filled with mineral wool and 10-15 mm plaster b/s. Both leaves resting on elastic bands. 15 mm elastified polystyrene	230	D_{nTA}* 61 dB * 100-5000 Hz	62 dB	60 dB
Sweden	200 mm homogenous on-site cast concrete	200	R'_w + C 57 dB	56 dB	54 dB
Turkey	gypsum Plaster b/s+ gypsum board + Metal Profile + 50 mm Glass wool+ 100 mm Concrete Hollow Block	180	R'_w 49 dB (calculated)	48 dB	47dB
UK	100 mm solid aggregate (1500kg/m3) block (cavity wall) with 75 mm cavity, 8 mm render coat with 12.5 mm gypsum board, wall ties Type A	320	$D_{nT,w}$+C_{tr} 53 dB	60 dB	56 dB

Country	Wall Description	Approx. Total Width [mm]	Typical Airborne Sound Insulation		
			Country descriptor (100-3150 Hz)	D_{nTw} (100-3150 Hz)	D_{nTA} (50-5000 Hz)
Australia	Two leaves of 110 mm clay brick masonry with 50 mm cavity and 50 mm thick glass wool/ polyester insulation and 13 mm plasterboard fixed to studs b/s	300	$D_{nT,w}+C_{tr}$ 45 dB	49 dB	49 dB

Key *o/s = one room side; b/s = both room sides*

In relation to the range of finishes adopted in each country for these wall types, in central and southern European countries the most predominant was gypsum based plaster, of thickness 10 mm to 30 mm.

As already mentioned, the typologies of floors built in different European countries are very different from each other. The main differences involve the type of finishes adopted (wooden, tiles, etc…) and the way the floating floor is realized.

Table 11.2 shows the airborne sound insulation of some typical separating floors collected from the same countries as Table 11.1. In this case, the total width varies from 200 mm to 450 mm, while $D_{nT,w}$ varies from 49 dB to 59 dB.

If impact performance of floors is considered, it is more complicated to present characteristic impact noise data for typical constructions. This is partly due to the fact that workmanship errors are more significant on impact floors performance than on the airborne sound insulation performance. In this case only a few examples are shown in Table 11.3. The indicated typical values are valid for floor constructions without any significant workmanship errors.

Table 11.2. *Example of current separating floor construction in different countries (typical values supplied by TU0901 members)*

Country	Description Floor construction	Approx. Total Width [mm]	Typical Airborne Insulation		
			Country descriptor (100-3150 Hz)	D_{nTw} (100-3150Hz)	D_{nTA} (50-5000 Hz)
Croatia	floor covering + cement glazing + PE foil + EEP + reinforced concrete + plaster	240	R'_w 55 dB	53 dB	52 dB
Czech Republic	180-250 mm concrete slab, mineral wool or elasticised polystyrene 20-40 mm, PE membrane, concrete or anhydrite layer 50 mm	250 -340	R'_w 58 dB	57 dB	55 dB
Denmark	Hollow concrete elements, weight 440 kg/m², with wooden floor on joists on elastic supports ($\Delta L_w \geq 20$ dB and $\Delta R_w \geq 3$ dB)	400-450	R'_w 56 dB	Not available	Not available

Country	Description Floor construction	Approx. Total Width [mm]	Typical Airborne Insulation		
			Country descriptor (100-3150 Hz)	D_{nTw} (100-3150Hz)	D_{nTA} (50-5000 Hz)
France	200 mm concrete with plastic floor covering	200 -300	$D_{nT'w}$+C 53dB	53 dB	53 dB
Germany	200 mm concrete with 55 mm floating floor, 20 mm mineral wool and 15 mm plaster	290	R'_w 56 dB	55 dB	54 dB
Iceland	240 mm on site cast concrete	240	R'_w 58dB	57 dB	55 dB
Italy	Beam and block system: 5-10 mm ceramic paving, 40 – 60 mm cement screed, 5-10 mm elastic layer, 200 mm hollow clay blocks + 40 mm concrete slab, and 15 mm plaster	320	R'_w 51 dB	49 dB	49 dB
Lithuania	50-60 mm sand cement screed, 20-50 mm mineral wool,25-50 mm sand (1400 kg/m3) and 220 mm reinforced hollow concrete slab	340	D_{nTw} 55 dB	54 dB	53 dB
Netherlands	240 mm concrete + 20 mm floating material + 50 mm anhydrite or 65 mm screed	320	R'_w+C 58 dB	59 dB	57 dB
Norway	260 mm massive concrete with parquet floor on 3mm ethafoam on top. Total	280	R'_w 55 dB	54 dB	53 dB
Poland	220 mm reinforced concrete slab + 50 mm thick concrete screed on a layer of 20 mm EPS-T polystyrene and 30 mm EPS polystyrene	320	R'_w+C 55 dB	55 dB	54 dB
Portugal	Reinforced concrete slab or beam-and-hollow clay blocks slab	250 -300	$D_{nT,w}$ 51 dB	51 dB	50 dB
Serbia	160 mm concrete slab + 70 mm floating floor	230	R'_w 55 dB	54 dB	53 dB
Slovakia	200 mm reinforced concrete slab + 40 mm mineral wool + 40 mm	280 -300	R'_w 58 dB	57 dB	55 dB
Slovenia	200 mm reinforced concrete slab + 60 mm concrete screed on thin PVC foil and 40 mm mineral wool	300	R'_w 60 dB	59 dB	57 dB
Spain	15 mm laminated wooden floor on 2 mm foam, 85 mm screed on 5 mm polyethylene, 300 mm grid floor with concrete blocks, 15 mm wet plaster finish	360	D_{nTA} * 54 dB * 100-5000 Hz	54 dB	53 dB

Country	Description Floor construction	Approx. Total Width [mm]	Typical Airborne Insulation		
			Country descriptor (100-3150 Hz)	D_{nTw} (100-3150Hz)	D_{nTA} (50-5000 Hz)
Sweden	250 mm homogenous on-site cast concrete + 15 mm parquet on 3 mm foam	250	R'_w+C 59 dB	58 dB	56 dB
Turkey	14 mm laminated parquet + 2 mm mattress + 60 mm screed + geotextile fabric + 25 mm mineral wool + 180 mm reinforced concrete + 40 mm mortar + gypsum plaster	300	R'_w 53 dB (calculated)	52 dB	51 dB
UK	65 mm min sand cement screed+ 6 mm rubber isolation layer + 150 mm min precast concrete plank (300 kg/m2) + 150 mm min ceiling void + 12.5 mm plasterboard ceiling	380	$D_{nT,w}+C_{tr}$ 51 dB	55 dB	54 dB
Australia	150 mm thick concrete slab with 28 mm metal furring channels and 65 mm thick polyester insulation and 13 mm plasterboard fixed to furring channels	200	$D_{nT,w}+C_{tr}$ 45 dB	49 dB	49 dB

Table 11.3. *Example of impact sound on separating floor constructions in different countries (typical values supplied by TU0901 members).*

Country	Description Floor construction	Approx. Total Width [mm]	Typical Impact Noise
Austria	70 mm concrete screed 20 mm mineral wool TDPS 25/20 80 mm loose fill 20 mm mineral wool TDPT 20/20 147 mm CLT cross laminated timber 350 kg/m2	340	L'_{nTw} = 43 - 46 dB
Denmark	Hollow core concrete slab with wooden floor on joists on PE wedges on elastic supports ($\Delta L_w \geq$ 20 dB), with or without mineral wool in the cavity	400-450 mm	$L'_{n,w}$ = 46 - 52 dB
Italy	200-280 mm beam and brick floor (plastered 10 mm). 100-120 mm of lightened mortar. Impact insulation resilient layer. 60-80 mm under floor heating system (thermal insulation + cement screed with reinforcing wire mesh). Ceramic tiles or parquet floor	400-450 (350-400 without under floor heating system)	$L'_{n,w}$ = 50-55 dB ($L'_{n,w}$ = 53-58 dB without under floor heating system)
Slovenia	Wooden floor Concrete screed (60 mm) Thin PVC foil Layer of mineral wool (40 mm) Reinforced concrete slab (200 mm)	320	$L'_{n,w}$ = 53 dB

Country	Description Floor construction	Approx. Total Width [mm]	Typical Impact Noise
Spain	350 mm beam and block floor. Ceramic blocks. 10 mm plastered. Impact insulation layer. 5 mm polyethylene layer. 70 mm cement screed with 200x200 mm reinforcing wire mesh 3 mm PE foam 8 mm laminated wood	440	L'_{nTw} = 46 - 49 dB
Sweden	Timber joist floor with a heavy floating top floor and a resiliently suspended ceiling made of plasterboard (2 layers).	450	$L'_{n,w}$ = 49 - 50 dB
UK	150 mm precast floor with 65mm screed on isolation layer, supported by 100 mm LWA blockwork walls, 12.5 mm plasterboard ceiling on 150 mm metal frame	430	L'_{nTw} = 54 dB

11.3. Compendium of Typical Building Constructions

As it can be seen in the "Country Chapters" that can be found in volume 2 [2], there are many different building construction solutions all around Europe. Some of them comply to achieve very high acoustic performance and others just meet the sound insulation requirements. The aim of this "compendium" is to collect and summarise the typical separating walls and floors presented in the "Country Chapters". To make the structure clear and as straightforward as possible, the constructions are presented in two different sections entitled WALLS and FLOORS respectively.

11.3.1. Walls

11.3.1.1. Heavy-weight walls over interrupted floor structures

In some European countries, interrupted structures are commom in single family attached houses or row houses, where each wall is a supporting wall. With this type of structure it is possible to achieve the highest level of sound insulation. The partition consists of two walls separated by a cavity of at least 40 mm. In between both walls, neither connections nor ties are permitted. The concrete slab must be interrupted by the cavity. The only exceptions are the connections at the foundation level and the roof. The concept significantly reduces flanking transmission. The system assures enhanced acoustic comfort between row houses for surface masses of the composing party walls ≥150 kg/m² in total.

The description and the picture (Figure 11.1) are taken from the Belgium chapter. This type of structure is used to fulfil the Belgium airborne sound

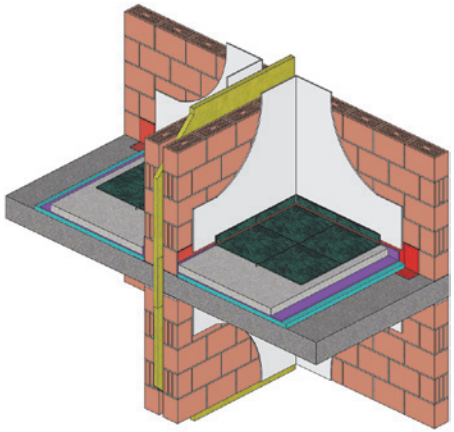


Figure 11.1. *Building with interrupted floor slabs and masonry cavity separating wall. [[2] - (Belgium)].*

insulation requirements $D_{nT,w} \geq 62$ dB. Similar solutions are used in other European countries: in Netherlands (see Figure 11.2), where the Building Decree (standard) gives the requirements for sound insulation between flats $R'_w \geq 52$ dB; in the UK where the building acoustic requirements are different for England, Wales ($D_{nT,w}+C_{tr} \geq 45$ dB) and for Scotland ($D_{nT,w} \geq 56$ dB); in Germany to fulfil the sound insulation requirement $R'_w \geq 57$ dB for row housing; in Denmark many terraced houses have cavity party walls made from concrete, lightweight concrete or aerated concrete elements (Figure 11.3), that ensure a sound reduction index $R'_w \geq 55$ dB, and if all constructions and junctions are made correctly, much higher performance may be obtained.

Typical new terraced houses have cavity walls made from masonry. Mainly calcium silicate, autoclaved aerated concrete (AAC) or lightweight concrete blocks and bricks are used. The surface mass of the two walls ranges from m' = 100 to 300 kg/m² (each). The cavity is typically between 30 and 50 mm and usually filled with mineral wool.

Typical cavity walls in Dutch terraced house, shown in Figure 11.2, are:

- 120 or 150 mm limestone, cavity 60 or 50 mm or 'light' precast concrete (both with a density of 1750 kg/m³) (i.e. 210 kg/m² or 265 kg/m² for each cavity leaf).

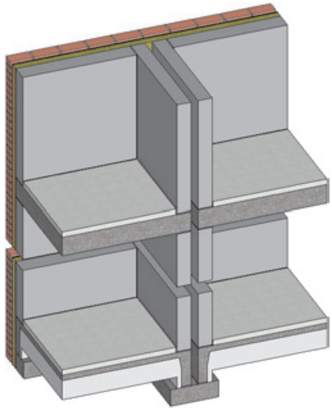


Figure 11.2. *Ground floor and first floor details of a Dutch cavity wall in terraced houses. [[2] - (Netherlands)].*

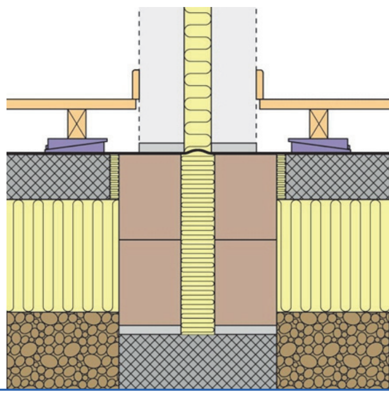


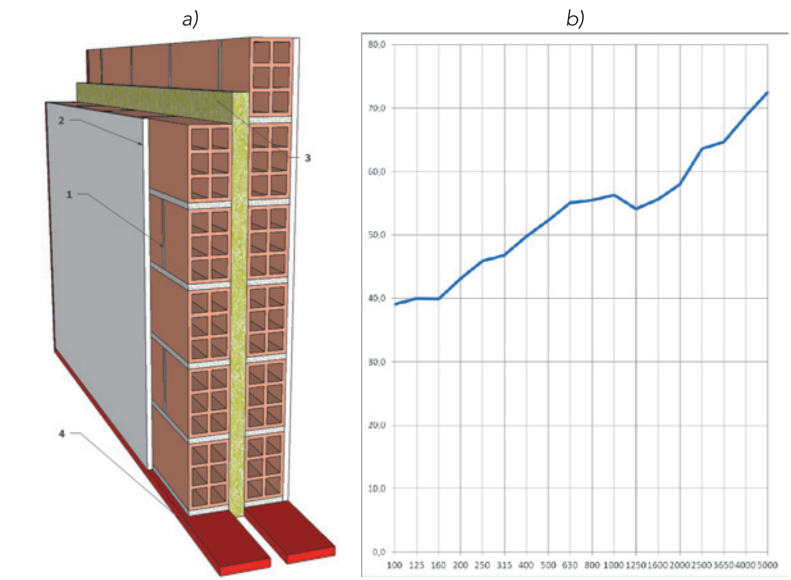
Figure 11.3. *Example of Danish heavy cavity wall construction for new terraced housing fulfilling the Danish Building Regulations 2010. Cross section through party wall showing the foundations. [[2] - (Denmark)].*

- 90 or 100 mm precast concrete (≈2400 kg/m^3) with a cavity of 40 mm, (i.e. 215 or 240 kg/m^2 for each cavity leaf);
- 120 or 140 mm concrete (2300 kg/m^3) with a cavity of 60 or 80 mm (made at location) (i.e. 276 or 322 kg/m^2 for each cavity leaf).

11.3.1.2. *Heavy-weight walls and continuous floor structures*

Cavity walls

Masonry cavity walls on continuous slabs are very common in apartment blocks in Europe. Typically, the party wall between two apartments or row houses consists of two leaf masonry walls separated at least 40 mm, with a mineral wool layer. Between both walls, no connections or ties are allowed at all. In some cases, specific acoustic isolation strips are applied below and on top of each masonry leaf. This allows the separating wall to behave as an acoustic double wall even with the continuous concrete slab. Figure 11.4 shows an example of a common cavity wall used in Spain to comply with the sound insulation requirements between dwellings, $D_{nT,A} \geq 50$ dB. This



1. 80 mm hollow ceramic brick (240x115x80)
2. 10 mm plaster on both sides

$D_{nT,A}$ = 54 dBA

$D_{nT,w\ 100\text{-}5000}$ = 55 dB

1. Cavity: 40 mm wide fully filled with mineral wool. 70 kg/m^3 density
2. Elastified elastic polystyrene (EEPS) band under brick wall and above it. 15 mm wide

Figure 11.4. *Building with continuous floor slabs and acoustic strip under a masonry cavity separating wall. [[2] - (Spain)].*

type of walls are non-loadbearing and are usually made of clay blocks with a density of 930 kg/m^3.

A similar construction technique, without the strips under and above the walls, has been also used in Italy to achieve the sound reduction index $R'_w \geq 50$ dB. Now the preferred solution consists of a layer of hollow bricks 80 mm thick (with a density between 800 and 900 kg/m^3) and a layer of semi-full bricks 120 mm thick (with a density between 800 and 1000 kg/m^3), plastered with 10-15 mm of mortar on both sides and on one side of the cavity. In the cavity there is 40-50 mm of mineral wool and 20-30 mm of air (Figure 11.5).

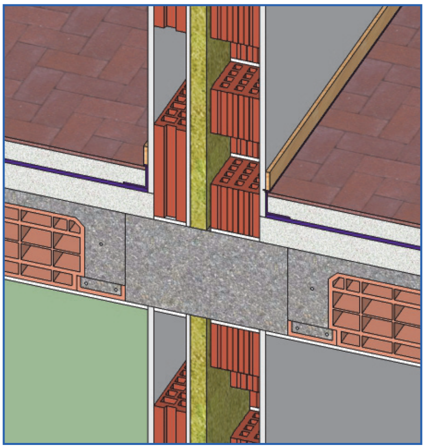


Figure 11.5. *Building with continuous floor slabs and a masonry cavity separating wall. [[2] - (Italy)].*

Another variation of this type of masonry wall, used in Portugal is a double wall built with “thermal” blocks, each layer 200 mm thick, plastered with 20 mm of mortar on both sides, with an air cavity of 30 mm containing thermal insulation of extruded polystyrene. This ensure to meet the sound insulation minimum requirement given in Decreto-Lei 96/2008, $D_{nT,w} \geq 50$ dB (Figure 11.6).

In the BBRI (Belgian Building Research Institute) Technical Notes, two different solutions are described, which use acoustic strips.

In both of the solutions the party wall between two apartments or row houses consists of two semi-heavy walls (each at least 125 kg/m^2, e.g.

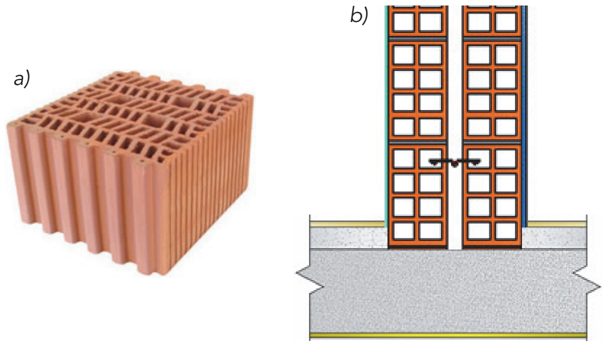


Figure 11.6. a) Example of thermal and acoustic block;
b) Wall-floor joint [[2]- (Portugal)].

140 mm bricks) separated by a cavity of at least 40 mm. Between both walls, no connections or ties are permitted.

In one case specific acoustic strips are applied below and on top of all load-bearing walls. This allows the double wall of the party wall to behave as an acoustic double wall even with the continuous concrete slab (Figure 11.7).

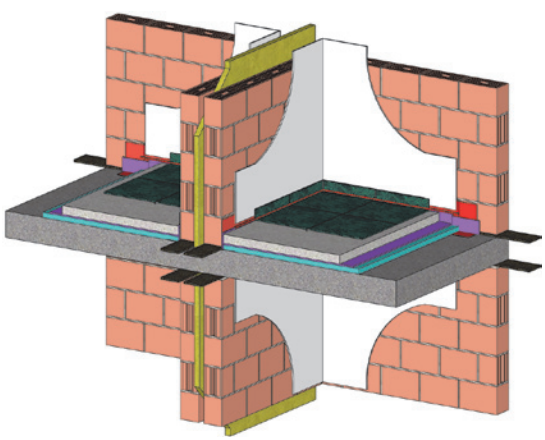


Figure 11.7. Building with continuous floor slabs, acoustic strip and semi-heavy load bearing double walls. [[2] - (Belgium)].

In the other BBRI solution the party wall between two apartments or row houses consists of two semi-heavy walls (each at least 125 kg/m², e.g. 140 mm bricks) separated by a cavity of at least 40 mm. Between both walls, no connections or ties are allowed at all. Specific acoustic strips are applied below and on top of all load-bearing walls. This allows the double wall of the party wall to behave as an acoustic double wall even with the continuous concrete slab (Figure 11.8).

In the UK the most common form of separating wall are cavity blockwork representing 65% of all walls. For cavity walls the core construction is two leafs of 100 mm blockwork separated by a cavity (Figure 11.9). Wall ties are

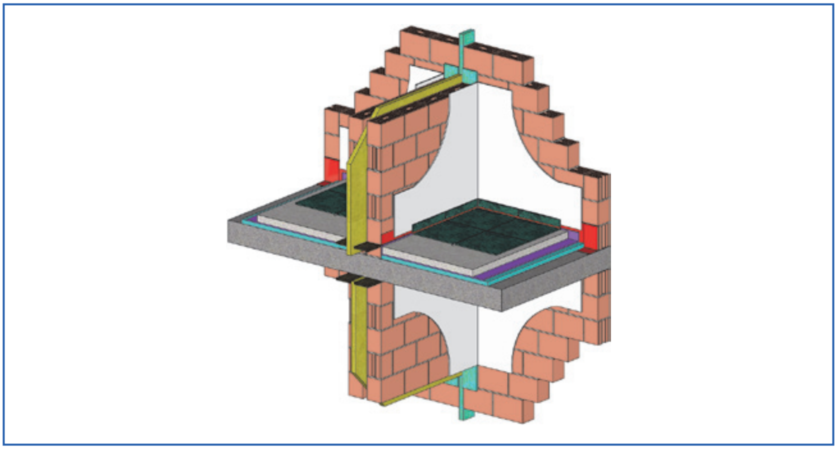


Figure 11.8. *Building with continuous floor slabs, acoustic strips and semi-heavy not-load bearing double walls [[2] - (Belgium)].*

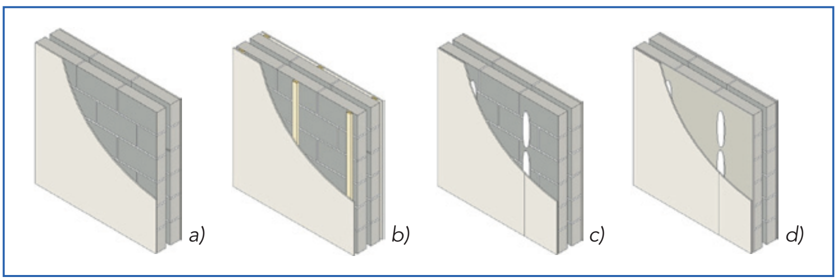


Figure 11.9. *Typical blockwork cavity separating walls found in the UK: a) plaster finish ; b) strap and lined with gypsum board ; c) gypsum board on dabs ; d) 8 mm parge coat with gypsum board on dabs. [[2] - (U.K.)].*

inserted in cavity walls to brace and stiffen the wall leafs for structural reasons. However, the structural connection formed by the ties can lead to a reduction in sound insulation performance. Hence specific "Type A" party wall ties must be used. Typically in 2013 most cavity masonry blockwork separating walls now have 100mm cavities and are fully filled with mineral wool to reduce cavity heat loss, which also improves sound insulation performance. This type of wall can be used both with continuous and interrupted slab.

In Hungary for walls separating two neighbouring dwellings, 250 mm wide HM-250 sand-lime blocks are used (density 2000 kg/m^3), with 10 mm plaster on both sides. In this case the walls should be built on a 4-6 mm thick resilient layer made of agglomerated cork or elastic-cork to avoid rigid joints. The laboratory value of airborne sound insulation of a wall constructed from these bricks is 56 dB. With the resilient under-layer the field value is ensured to be above the requirement R'_w > 51 dB, that is expressed in field value in the case for walls separating dwellings.

Typical sound insulation performance of UK blockwork walls.

	$D_{nT,w}$	Ctr
Aircrete 100 mm block twin leaf wall, 75 mm cavity	59 dB	–6 dB
LWA 100 mm block twin leaf wall, 75 mm cavity	60 dB	–8 dB
Dense block aggregate twin leaf wall, 75 mm cavity	61 dB	–7 dB

Note: all walls have 8 mm parge coat with 12.5 mm gypsum board on dabs

Solid walls

Monolithic walls, in typical Italian partitions used between dwellings, are composed of expanded clay and concrete blocks characterized by an apparent density between 1200 and 1400 kg/m^3, plastered with 10-15 mm of mortar on both sides (Figure 11.10). Other types of monolithic walls consist of clay blocks, frequently with big holes filled with concrete, or with additional components in order to improve the thermal insulation.

In the Netherlands, terraced houses and apartment buildings use solid walls made of concrete, or limestone (Figure 11.11) and are used to fulfil the sound insulation requirements. Typical solid walls (in terraced house and apartments) are the following:

- 300 mm limestone (1750 kg/m^3 or 525 kg/m^2) or 250 mm heavy limestone (2200 or 2300 kg/m^3 or 575 kg/m^2)
- 230 mm or mostly 250 mm of concrete (2300 kg/m^3) or 220 mm precast concrete (≈2400 kg/m^3) with a mass of 529 , 575 respectively 525 kg/m^2

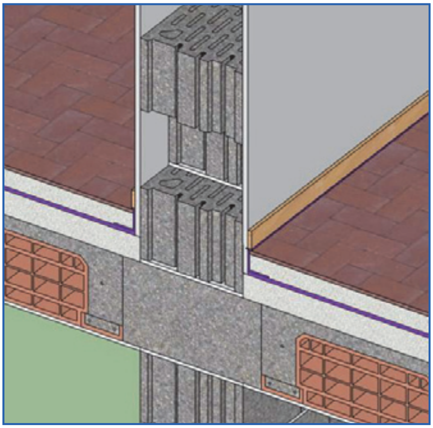


Figure 11.10. Italian monolithic wall with expanded clay and concrete blocks. [[2] - (Italy)].

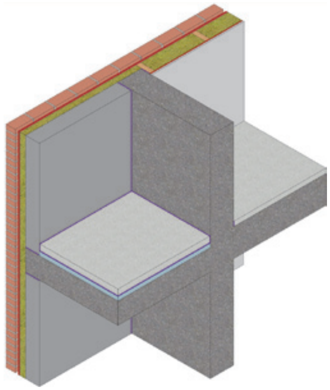


Figure 11.11. Detail of Dutch solid separating wall [[2] - (Netherlands)].

Solid walls made from concrete elements are used in Denmark as party walls in terraced housing and multi-storey housing to ensure a sound insulation $R'_w \geq 55$ dB, as required in the Danish Building Regulations 2010 (Figure 11.12).

In Hungary the most common solution is to use sand-lime bricks. Due to their high density (1400-2000 kg/m^3) these bricks can be used on their own, without any additional layers (except for plaster).

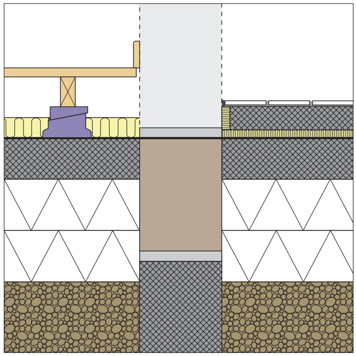
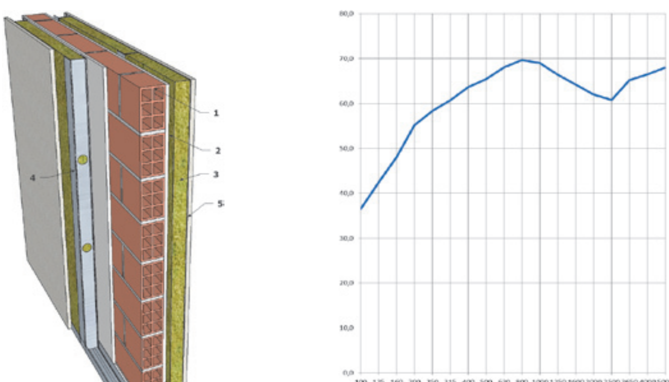


Figure 11.12. *Example of Danish heavy solid wall construction for new terraced housing fulfilling the Danish Building Regulations 2010. [[2] - (Denmark)].*

Lined walls

Spanish masonry between independent linings walls consists of a single leaf masonry wall with one or two layers of gypsum boards fixed to independent steel frames (Figure 11.13). Each independent lining in most



$D_{nT,A}$ = 61 dBA
$D_{nT,w}$ 100-5000= 55 dB

1. 70 mm hollow brick wall (70 kg/m²)
2. 10 mm plaster on both faces
3. 50 mm mineral wool
4. 48 mm studs
5. 15 mm plasterboard

Figure 11.13. *Masonry between independent panels; b) Typical airborne sound insulation. [[2] - (Spain)].*

cases increases the insulation of the masonry wall by around 10 dB. Using linings is also a common way to enhance the sound insulation performance of existing buildings.

In Belgium a similar solution is proposed. The party wall between two apartments or row houses consists of a load bearing wall and a gypsum board lining (of at least 2 x 12.5 mm gypsum) on a separated (or vibration disconnected) metal stud frame (Figure 11.14). The cavity width between the gypsum boards and the wall should be such that the mass-spring-mass resonance falls below 50 Hz. The cavity needs to be filled with mineral wool or similar. To optimise thermal inertia of the apartment as well as to limit the vertical flanking transmission, it is interesting to have a concept such that half of the apartment party walls are stone, the other half are gypsum board lining. This building concept is popular as it allows for party walls with a limited width compared to the other building systems.

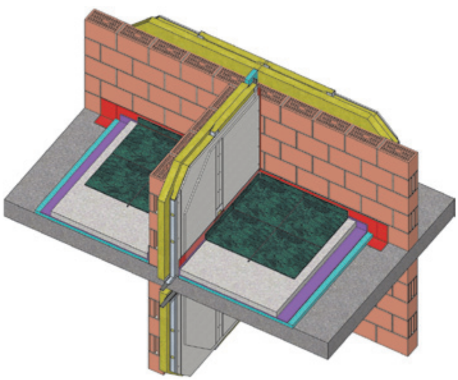


Figure 11.14. *Building with continuous floor slabs and a party wall with a single load bearing wall with gypsum board linings [[2]- (Belgium)].*

11.3.1.3. Light-weight walls

Many European countries developed light-weight wall constructions fulfilling the sound insulation requirements between dwellings. This section shows either steel or timber frame walls that could be considered a good overview of the different approaches across Europe.

In Austria the standardized sound level difference $D_{nT,w} \geq 55$ is the minimum requirement. Measuring the sound insulation in a multi-family house where the walls and floors had been constructed according to the Figures 11.15, 11.16 and 11.17 the following weighted standardized sound level differences were found: $D_{nT,w}$ = 64 dB between adjacent rooms and $D_{nT,w}$ = 56 dB between rooms located on top of each other.

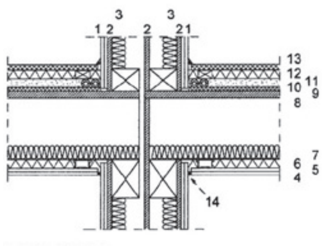


Figure 11.15. Connection between wall separating flats and floor (vertical section) [[2] - (Austria)].

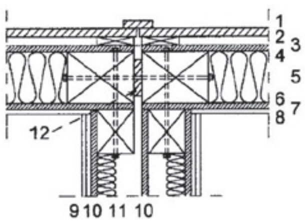


Figure 11.16. Connection between outer wall and wall separating flats (horizontal section) [[2] - (Austria)].

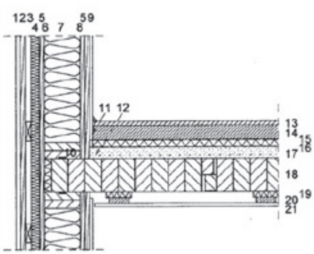


Figure 11.17. Connection between outer wall and floor (vertical section) [[2] - (Austria)].

In Belgium BBRI publishes Technical Notes and also refers to light weight structures. The party wall consists of a double gypsum block party wall (Figure 11.18). The composing walls must have different thicknesses. Cavity distance and surface mass of the blocks should be chosen in such a way that the mass-spring mass resonance shifts below 50 Hz. The load bearing brick wall should be interrupted at the cavity of the party wall to avoid horizontal flanking transmission. The (ceiling) concrete slab should have a surface mass of more than 650 kg/m² to limit the vertical and horizontal flanking transmission. Absolute attention should be paid to the decoupling of the gypsum blocks of the surrounding structure so as to maintain the acoustic double wall behaviour of the party wall.

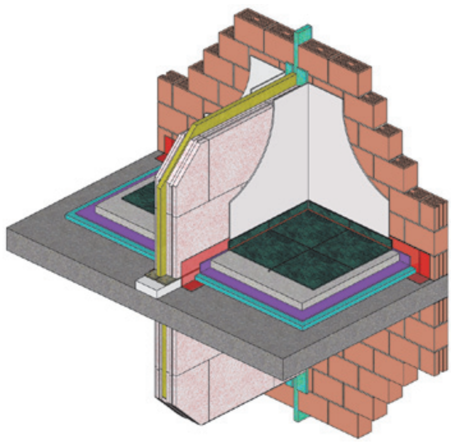
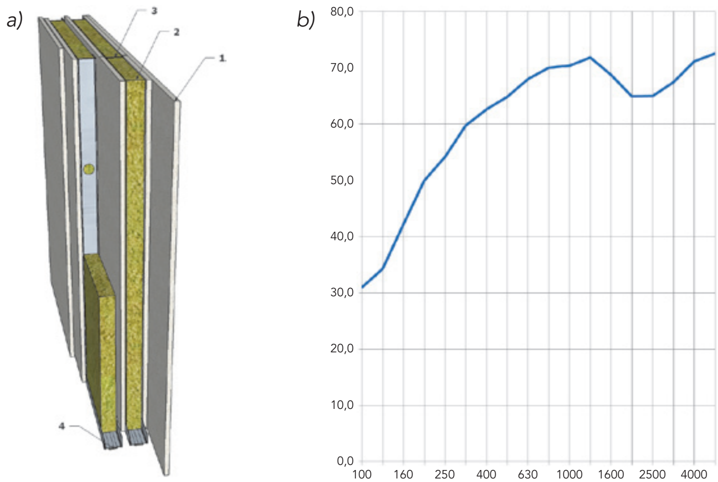


Figure 11.18. *Building concepts continuous floor slabs and a party wall with non load bearing walls of gypsum blocks. [[2] - (Belgium)].*

Spanish Basic Document DB HR (Protection against noise) also proposes a light-weight separating wall to fulfil the airborne insulation requirements. Steel framed walls with absorbent materials are not as traditional as masonry walls, but metal framed walls are increasingly being used in Spanish buildings. Type 3 walls (Figure 11.19) are two leaf gypsum based board walls, consisting of two 12,5 mm plasterboards screwed directly to double metal studs. Absorbent material batts must be placed between the studs. Typical studs are 48 mm or 70 mm. These walls are non-loadbearing walls built on top of a continuous concrete structure.



1. 12,5 mm plasterboard
2. 50 mm mineral wool
3. 48 mm studs
4. Elastic PE band

$D_{nT,A}$ = 56 dBA
$D_{nT,w\ 100\text{-}5000}$= 56 dB

Figure 11.19. *a) Separating wall. Type 3. Framed walls with absorbent materials; b)Typical airborne sound insulation. [[2]- (Spain)].*

Depending on the height of the room and type of stud, the studs must be tied to ensure structural safety, which results in a decrease in sound insulation of approximately 8 dB. In this sense, it is better to seek the advice of the manufacturer or a consultant to avoid having to tie the studs.

In Denmark to ensure a sound reduction index $R'_w \geq 55$ dB in multi-storey housing, heavy floors could be combined with light-weight party walls. The light-weight wall is plasterboard wall with double framework (Figure 11.20). The surface mass of the plasterboards on each side should be approximately 20 kg/m^2.

In the Netherlands timber-based buildings (TBB) are in use for terraced houses, always as a cavity wall (Figure 11.21).

Light-weight timber frame constructions in Belgium (Figure 11.22) have seen an expansion towards row houses and even small apartment constructions. Recent research in the BBRI led to significant improvements to these constructions, especially in their low frequency performance. First

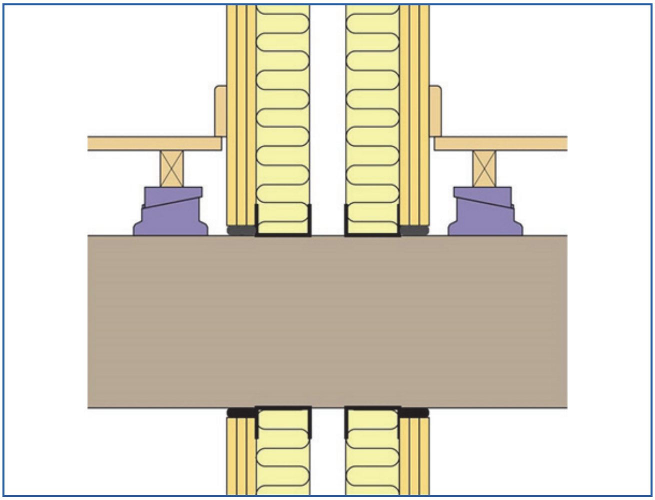


Figure 11.20. *Example with a heavy floor combined with a light-weight party wall. [[2]- (Denmark)].*

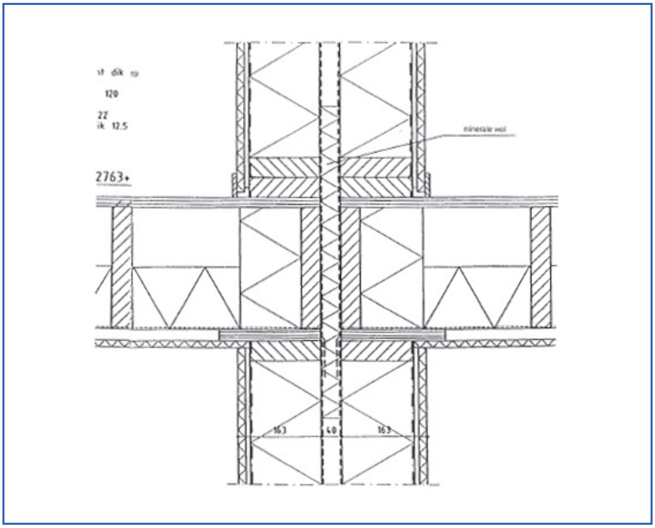


Figure 11.21. *Timber based building with cavities of 200 till 300 mm detail of first floor see (SBR 2003) for Class 3 and class 2 (NEN 1070:1999) [[2] - (Netherlands)].*

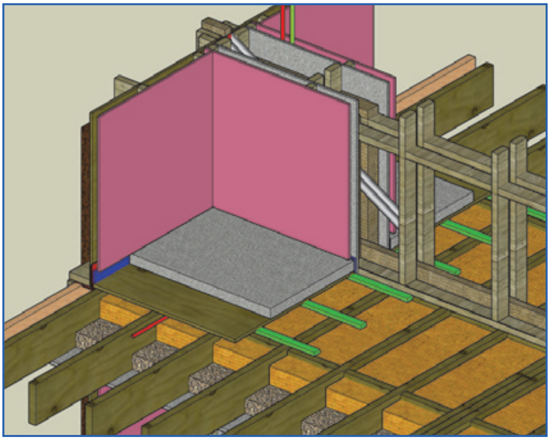


Figure 11.22. Light weight timber frame constructions [[2] - (Belgium)].

new party walls were developed ($R'_w + C_{50\text{-}3150} > 64$ dB), and in a second phase, new floors were developed ($R'_w + C_{50\text{-}3150} > 65$ dB and $L_{nT,w} + C_{I,50\text{-}2500} < 48$ dB).

In the UK timber frame separating walls are normally composed of two panels formed from timber 'studs' supported by timber sole plates and are closed by a head plate. The studs are typically 100 x 50 mm with the frames separated by a 30-50 mm cavity. Frames are sometimes strengthened by a sheathing board, which is mounted on the cavity side. Mineral wool is commonly placed on each side of the twin frames and typically minimum 60 mm thick. Timber frame separating walls are commonly finished with two or more layers of gypsum based board with staggered joints. The thickness of each layer ranges from 10 mm to 19 mm and typical two layer linings are 19 mm and 12.5mm gypsum board or 2 layers of 15 mm gypsum board, each side. Timber frame separating walls are either sheathed (Figure 11.23 a) or non-sheathed (Figure 11.23 b) (using minimum 9 mm OSB boarding), depending on structural racking strength requirements and sheathed walls are now the most common construction.

Typical sound insulation performance of UK timber separating walls.

Construction	Airborne $D_{nT,w}$	C_{tr}
Timber non-sheathed wall (240 mm between gypsum layers)	61 dB	–9 dB
Timber sheathed wall (240 mm between gypsum layers)	63 dB	–10 dB

Note: all walls have 60 mm mineral wool (each side) and 2 x 15 mm gypsum board.

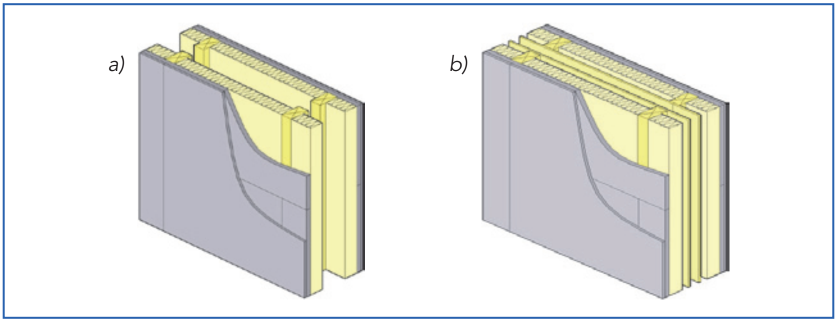


Figure 11.23. *Examples of twin frame timber frame separating walls non sheathed (a) and sheathed (b). [[2] - (U.K.)].*

11.3.2. Separating floors

11.3.2.1. Heavy-weight floors structure

Heavy-weight separating floors are popular all over the Europe and to obtain a good sound insulation performance, it is common to use floating floors both in continuous and separated structures. There are several types of heavy weight structures, for example in Estonia impact sound insulation requirement, $L'_{n,w} \leq 53$ dB, is usually ensured by concrete floating floors on hollow-core panels or on monolithic concrete slab (Figure 11.24). The weighted normalized impact sound pressure level is typically $L'_{n,w} \leq$ 48-50 dB but also exceptionally good results occurred $L'_{n,w} \leq 45$ dB.

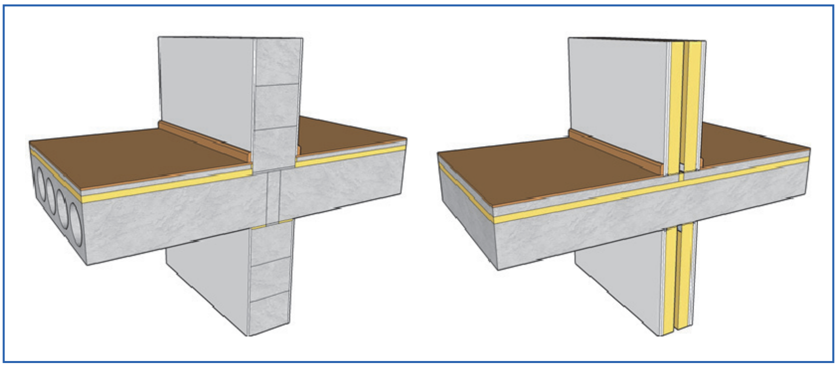
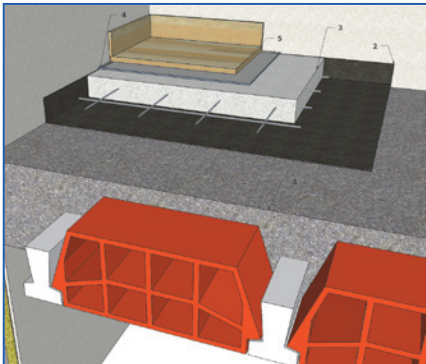
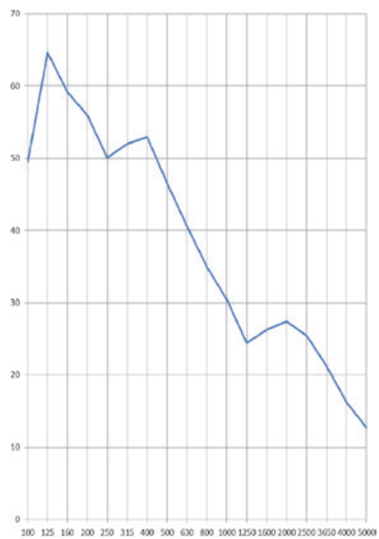


Figure 11.24. *left) Massive wall structure and concrete floating floor on hollow-core panels; right) Lightweight wall structure and concrete floating floor on monolithic concrete slab [[2] - (Estonia)].*

In Spain beam and block floors and grid floors are the most common. Floor blocks can be either ceramic or light aggregate concrete. Surface mass is 350 kg/m^2 in average. To control impact noise and fulfil the impact sound insulation requirements, $L'_{nT,w} \leq 65$ dB, it is recommended to build a floating floor consisting of at least 50 mm cement screed and a resilient layer (20 mm mineral wool, 5 mm polyethylene, 20-30 mm EEPS) (Figure 11.25, 11.26). Flanking strips have to be used in the perimeter to avoid flanking structure borne sound. This solution is used in many European countries such as Italy ($L'_{n,w} \leq 63$ dB), Germany ($L'_{n,w} \leq 53$ dB in multi-family houses, $L'_{n,w} \leq 48$ in semi-detached and row houses), Netherlands ($L_{nT,A} \leq 54$ dB), Belgium ($L'_{nT,w} \leq 50$ dB, EAC) and Portugal ($L'_{nT,w} \leq 50$ dB).

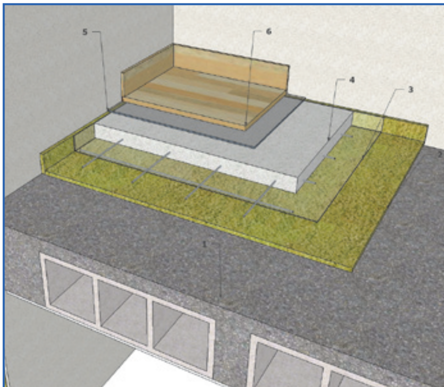


1. 350 mm beam and block floor. Ceramic blocks. 10 mm plastered.
2. Impact insulation layer. 5 mm polyethylene layer.
3. 70 mm cement screed with 200x200 mm reinforcing wire mesh.
4. 3 mm PE foam.
5. 8 mm laminated wood Skirting board.

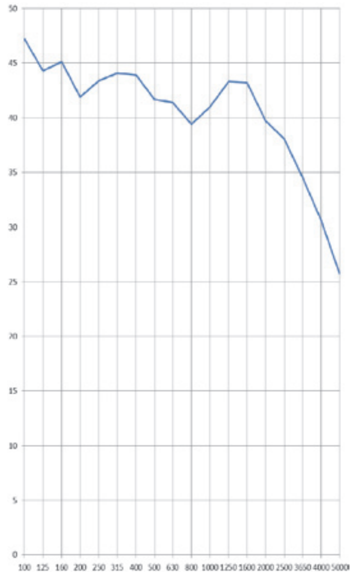


$L'_{nT,w} = 49$ dB

Figure 11.25. *Example of a typical beam and block floor with a floating floor consisting of a screed on a polyethylene layer [[2] - (Spain)].*



1. 350 mm grid floor with concrete blocks. 10 mm plastered.
2. Impact insulation layer. 15 mm mineral wool.
3. 3 mm polyethylene.
4. 50 mm cement screed with 200x200 mm reinforcing wire mesh.
5. 3 mm PE foam.
6. 8 mm laminated wood Skirting board.



$L'_{nT,w}$ = 49 dB

Figure 11.26. *Example of a typical grid floor with a floating floor consisting of a screed on mineral wool [[2] - (Spain)].*

In Denmark most new apartment houses are made from concrete elements. It is recommended that slabs have a surface mass of 440 kg/m^2. The wooden floor finish on joists on PE floor wedges must have an impact sound pressure level reduction of $\Delta L_w \geq 20$ dB. The wall is made from 200 mm concrete wall elements (Figure 11.27). This solution ensures compliance with the impact sound insulation requirements given in the Building Regulations 2010: $L'_{n,w} \leq 53$ dB.

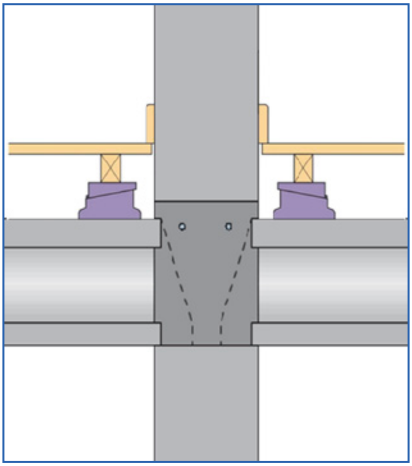


Figure 11.27. Example of heavy wall / heavy floor construction for new apartment houses fulfilling the Danish Building Regulations 2010. [[2] - (Denmark)].

The minimum impact sound insulation requirements for new build houses are $L'_{nT,w}$ ≤62 dB in England and in Wales and $L'_{nT,w}$ ≤56 dB in Scotland. The most common form of separating floor utilises precast concrete floors slabs typically 150 mm to 200 mm thick with a minimum mass per unit area of 300 kg/m^2. Floor finishes may include floating screeds isolated on resilient layers, floating timber floor finishes on resilient battens or cradles with various timber or metal frame ceiling supports.

Most common separating precast concrete floor performance in UK.

Construction	Airborne $D_{nT,w}$	Ctr	$L'_{nT,w}$
150 mm precast floor with 65 mm screed on isolation layer, supported by 100 mm LWA blockwork walls,	59 dB	–6 dB	54 dB
12.5 mm plasterboard ceiling on 150mm metal frame			

In Finland the minimum requirements for airborne sound insulation and impact noise are $R'_w \geq 55$ and $L'_{n,w} \leq 53$. Typical heavy weight solutions (Figure 11.29) to fulfil these requirements are:

In Hungary the most common heavyweight separating floor construction is a beam and block system with floating floor. The height of the beams with the hollow ceramic or concrete blocks is 190 mm, which is covered with 40, 60 or 85 mm thick concrete layer (depending on the design). The impact sound

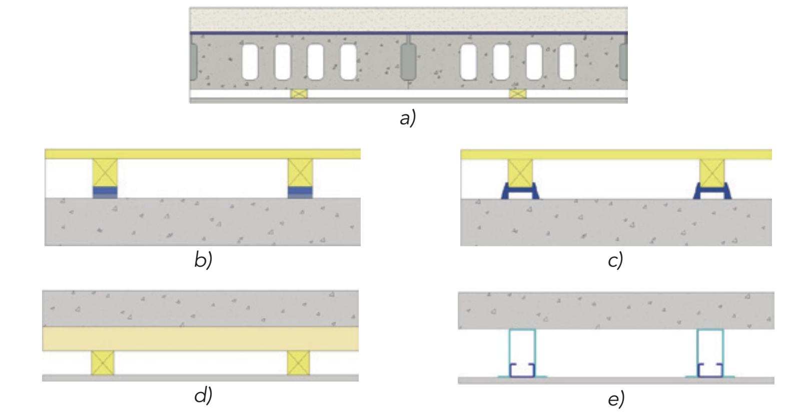


Figure 11.28. *Examples of precast concrete separating floors with a) screed finish on isolating layer; b) use of resilient flooring battens; c) use of resilient cradle floor deck systems; d) Timber counter strapped ceiling frames; e) metal frame ceilings. [[2] - (U.K.)].*

- Floors: hollow-core slab 370 mm or 270 mm + concrete 50 mm, surface material parquet + Tuplex flexible underlay (or better).
- Roof: hollow-core slab 270, 320 or 370 mm.
- Walls (between dwellings and dwelling-corridor) : concrete 200 mm.
- Exterior walls: concrete sandwich elements or structure with concrete inner envelope 150 mm.

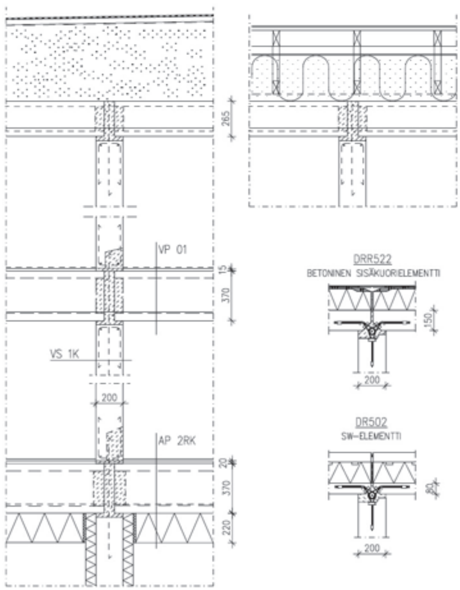


Figure 11.29. *Details of typical separating floor. [[2] - (Finland)].*

insulation layer is typically 30 mm thick mineral wool or a double layer consisting of a load bearing extruded polystyrene board, a thin insulation foil, and 30 mm thick mineral wool layer. In the latter case the polystyrene layer is used for hiding the pipes. The floating layer is typically 60 mm screed with 5 mm thick PE foam perimeter isolating strip. If the top layer is laminated floor, it is laid on 3 mm thick felt or PE layer, whereas the ceramic tiling is glued directly onto the screed (Figure 11.30). As the properly built floating floor increases the airborne sound insulation by 3-5 dB, the resulting floor construction satisfies both the airborne (R'_w+C > 51 dB) and the impact (L'_{nw} < 55 dB) sound insulation requirements for the separating floor.

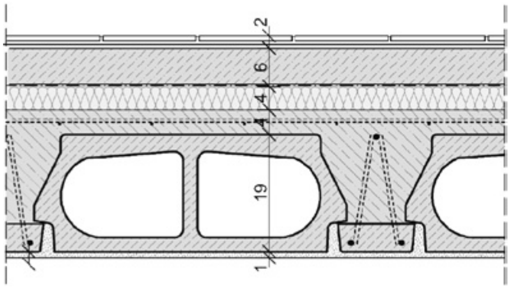


Figure 11.30. *Cross-section of the most typical heavyweight floor construction, the layers from top to bottom: floor tiling, screed, foil, impact sound insulation layer, beam-and-hollow-block floor system with concrete upper layer, parge coat. [[2] - (Hungary)].*

11.3.2.2. Light-weight floor structure

Certainly heavy-weight constructions are widely used in Europe, however in some countries light-weight and timber based solutions are more common in some regions (e.g. Scotland - 70% is timber frame). More recently in some European countries lightweight constructions are increasingly being used. Some examples are shown in figures 11.31 to 11.33.

In Norway for example row houses/attached houses are most commonly built with lightweight constructions (Figure 11.31).

Description of typical separating wall:

- 2 x 13 mm gypsum boards on separate studs with 70 mm insulation, 20-30 mm air cavity, 2 x 13 mm gypsum boards on separate studs with 70 mm insulation.

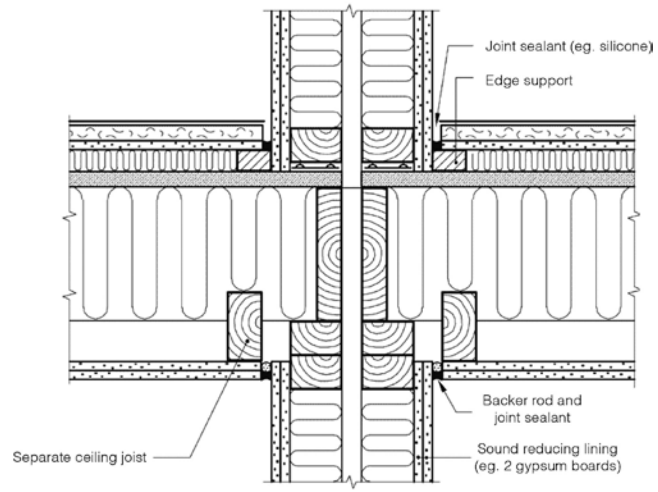


Figure 11.31. *Generic detail showing typical separating wall and floor and the junction between them in terraced housing [[2] - (Norway)].*

Description of typical separating floor:

- Lightweight floating floor (parquet, resilient layer, 22 mm flooring particle board, 20 mm mineral wool), load-bearing wood beams with mineral wool in cavity, 2 x 13 mm gypsum boards on separate beams or resilient bars/hangers.

The constructions will in most cases fulfil the minimum requirements, but complaints have been registered, especially where measured values for impact sound pressure levels are just within the requirements. The reason for this is most likely related to high levels in the frequency range 50-100 Hz, as the $C_{i,50\text{-}2500}$ adaptation term can be as high as +8 dB, resulting in $L'_{n,w} + C_{i,50\text{-}2500} > 58$ dB.

In the UK recently, timber core floor design has diversified into a variety of other materials and engineered solutions, such as engineered 'I-joists' and metal web joists. Depths are typically 220 mm to 302 mm for 'I-joists' and commonly 253 mm for metal web joists (Figures 11.32 and 11.33).

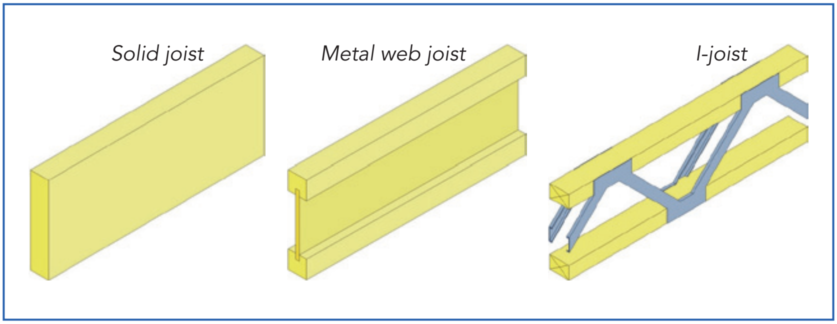


Figure 11.32. *Examples of separating floor joists [[2] - (U.K)].*

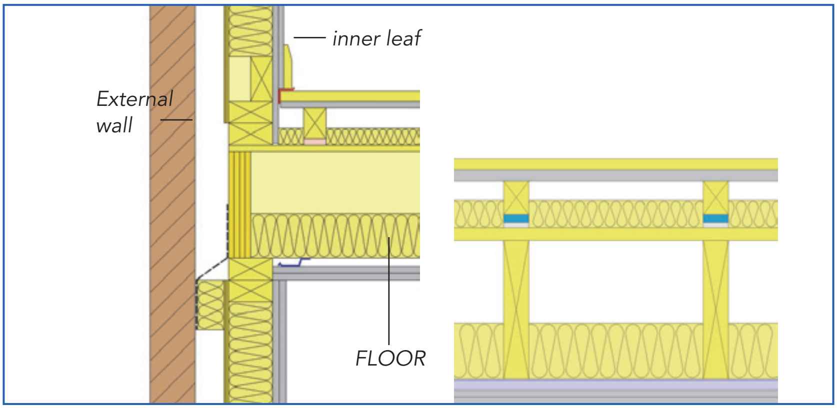


Figure 11.33. *Left: Junction with external wall Right: Section of separating floor [[2] - (U.K)].*

The floor is usually built using 16 mm resilient ceiling bars to support the ceiling, floating resilient battens with a layer of 19 mm gypsum and 18 mm wood fibre board above.

Typical sound insulation performance of UK timber separating floors.

Construction	Airborne $D_{nT,w}$	C_{tr}	$L'_{nT,w}$
18 mm board, 19 mm gypsum, 70 mm resilient battens, 25 mm insulation, 18 mm subdeck, 240 mm i-joist floor,	62 dB	–11 dB	53 dB
100 mm insulation, 16 mm resilient bars, 2 x 15 mm gypsum			

11.4. Acknowledgements

The authors of this chapter want to thank all COST TU0901 members for their input for Tables 11.1, 11.2 and 11.3 and for allowing reproducing contents from the corresponding Country Chapter in this "compendium chapter".

11.5. References

[1] *COST Action TU0901 «Integrating and Harmonizing Sound Insulation Aspects in Sustainable Urban Housing Constructions».* www.costtu0901.eu.

[2] Building acoustics throughout Europe- Volume 2: Housing and construction types country by country- (Figures and corresponding references can be found in chapters 1, 2, 5, 6, 7, 11, 13, 17, 18, 20, 25, 27 and 29).

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12

COST TU0901 Conclusions and Research Proposals

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CHAPTER 12 COST TU0901 Conclusions and Research Proposals

12.1. Conclusions

The European Union was founded to promote better integration and closer co-operation of the States and people in Europe. One of the most significant outcomes was the development of a single market and a legislative framework to ensure the free movement of people, goods, and services. The EU has also created a common policy in many other aspects such as marketing, agriculture and fishing.

Environmental noise problems have also been addressed by EU regulations in the Environmental Noise Directive (END, 2002) and the related END strategy paper "Research for a quieter Europe in 2020". It would be appropriate that in future, noise in dwellings is treated with similar importance, as surveys indicate that annoyance from neighbours and other indoor noise is of the same magnitude as noise from outdoors. After many years of an iterative process in developing National, CEN and ISO standards, COST Action TU0901 has produced for the first time a consensus for a future harmonized building acoustic approach for Europe, which could be a keystone in changes to come. This would not have been possible without the detailed discussions and collective input of multiple research institutes involved in TU0901.

However, it has been a significant challenge to reach consensus regarding the sound insulation and noise descriptors to be applied for evaluation of different acoustic qualities of dwellings and to define and create a proposal for an acoustic classification scheme for housing that could be adopted by member States. These issues have been the main objectives of COST TU0901 (http://www.costtu0901.eu/), which has provided an adequate framework for collecting a diversity of approaches, experiences and construction and sound insulation data. COST TU0901 has through the discussions and outputs been an exemplar of the EU motto "United in diversity".

After four years of close cooperation between researchers from all over Europe in the field of building acoustics, most outcomes correspond to what was planned when applying for the COST Action and when writing the MoU (Memorandum of Understanding). It is not without great efforts that the following sizeable tasks have been achieved:

- Proposing a harmonized set of sound insulation rating descriptors to be applied for dwellings and to be delivered to the standardization bodies.
- Producing guidelines for translating existing requirements and class criteria into the new proposed descriptors.
- Preparing a proposal for a harmonized acoustic classification scheme for dwellings.
- Developing a uniform questionnaire on annoyance from neighbour noise which can be correlated to objective - measured or calculated - sound insulation data.
- Preliminary results and input to guidelines on listening tests for assessment of subjective perception of noise in dwellings.
- Collecting and organizing a compendium of existing construction solutions in Europe, with acoustic performance data.
- Collecting typical design and workmanship errors and providing guidelines to avoid such errors concerning acoustic performance of buildings.

In addition, one of the key outcomes from TU0901 was the consolidation of a strong network of dedicated multi-disciplinary researchers belonging to universities, organisations, private and public institutions, companies and standardization bodies. This network represents many different sectors having interest in the sustainable improvement of acoustic performance of dwellings in Europe.

As a result of COST TU0901 discussions, several important research projects in different countries have been formed or supported. Some projects are mentioned below as interesting examples and pave the way for further research:

- The ERACO research project STAR (Sustainable Thermal Acoustic Retrofit) is a three-country ERACOBUILD project (BE-SE-UK) and was inspired via COST TU0901, where the project partners met each other. The project focuses on the technical compatibility of retrofit of dwellings between energy efficiency improvements and other technical issues such as sound Insulation and material synergies. The project rational is that due to the significant current focus on energy savings and that sound insulation is often counter-intuitive, there are risks that thermal insulation retrofitting reduces the sound insulation –opposite of what many people think–. STAR looks for the combined thermal and acoustic win-win solutions, innovative products and building details allowing a holistic approach to retrofit of buildings.

- Three national research projects are mentioned here as examples of research ideas originating in TU0901 objectives.
  - A Finnish Research Project (2011-2014) "User-Oriented Development of Sound Insulation in Buildings ÄKK" is aiming at providing better scientific basis to improve single number quantities used to describe sound insulation of buildings. The research is carried out both in laboratory and in the field and is a cross-scientific project combining building acoustics and environmental psychology.
  - A Swedish project Akulite (completed 2013) has focused on improving constructions for light-weight buildings based on extensive field and laboratory tests, including also field surveys on subjective evaluation.
  - A Turkish project (completed 2013) included extensive field studies aiming at preparing proposals for improved traffic noise spectra applied as reference spectra for improved facade sound insulation descriptors.

12.2. Research proposals and next stages

Based on COST TU0901 research findings and discussions, it is concluded that significant results have been obtained, but also that weak areas and additional problems have been found or become more evident. It is concluded that several issues need more scientific discussions and in-depth research to be developed. Out of many important issues needing further research, the following are highlighted:

- Are there different needs for low frequency range extension in airborne and impact sound insulation descriptors? Needs for heavy-weight and light-weight building solutions, respectively? This research must include subjective surveys.
- To investigate across Europe the implications on real housing (utilising field tests) of the extension to low frequencies for the proposed future harmonized criteria developed by TU0901, identifying if there are specific limitations on certain constructions and dwelling types, which are being designed for 2018/19 energy and carbon reduction requirements.

- Field surveys of neighbour noise annoyance. Proposal to utilise the TU0901 created housing occupant survey questionnaire to establish a European platform of acceptability and quality of life for levels of sound insulation. This would then provide a baseline for construction and product manufacturers to develop a series of optimized construction systems delivering an appropriate balance of material resource efficiency and an acceptable quality of life.
- Proposal to develop technical compatible solutions for future low carbon housing, delivering the thermal, acoustic and structural performance required for 2018/19.
- Develop further listening test methodologies to supplement under controlled, repeatable and reproducible conditions results from field surveys. Special attention to low frequencies is needed.
- Some tasks related to the low-frequency issue: Investigate vibration annoyance below 50 Hz for lightweight structures and consider adding such criteria in building regulations; Improve measurement and prediction methods; Clarify further the effect of low frequency inclusion on uncertainties of single number quantities (descriptors).
- Research providing knowledge –not just methodologies– on correlation between subjective evaluation (as rated by people) and objective sound insulation (as rated based on measurements or calculations).

Considering the existing building stock in Europe, it is foreseen that sustainable building retrofitting and development is necessary in the coming years. Research on the technical compatibility of the many aspects involved in retrofitting and acoustic performance of dwellings is undoubtedly a field of interest and a major challenge.

The TU0901 proposal for a classification scheme has been presented to standardization committees in ISO and CEN aiming at further development of the TU0901 proposal to become a European or even world-wide scheme, thus also reminding people and the building industry about the possibility of integrating the specification of acoustic conditions on equal terms with other qualities for new and renovated housing.

TU0901 members agree that EU citizens will benefit from quieter homes and from harmonized description of the acoustic performance of their dwellings, but it is also foreseen that due to technical, social, cultural, constructive and economic factors, there must be a long enough transition period before we can live in a "harmonized building acoustics Europe".

Now is the moment for legislators to open the debate on Building Acoustics European Policy based on the TU0901 findings, which could be seen as the seed for a future EU Acoustic Performance Directive for housing and a related strategy paper *"Research for quieter European homes in 2020"*.

We are on the way *"Towards a common framework in building acoustics throughout Europe"*.

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Annex.
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Annex

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"Building acoustics throughout Europe" is a summary of the work undertaken during four years of close co-operation and discussions between experts from 32 countries participating in COST Action TU0901 "Integrating and Harmonizing Sound Insulation Aspects in Sustainable Urban Housing Constructions".

"Building acoustics throughout Europe" is a two-volume publication. The contents of Volume 1, ***"Towards a common framework in building acoustics throughout Europe"***, range from the diverse existing situation in Europe concerning sound insulation requirements and classification schemes through subjective perception of neighbour noise to proposals for harmonized sound insulation descriptors and an acoustic classification scheme for dwellings. The book also includes overview chapters on typical European housing constructions, their design and acoustic performance and workmanship errors. Volume 2, ***"Housing and construction types country by country"*** consists of country chapters describing the national housing stock, construction types and related sound insulation performance in countries involved in COST TU0901.

The findings made by COST TU0901 and the co-operation established are excellent stepping stones for continued research and future development towards future quieter European homes.

"TU0901 has delivered a series of harmonization proposals, identified future research areas for industry and government and led to unparalleled knowledge exchange of which it has been an honour to be part of".

Professor Sean Smith, Chair of TU0901 WG3 Institute for Sustainable Construction, Edinburgh Napier University, UK

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